A FAST SOLUTION METHOD FOR MODELING THE RTM-PROCESS USING SIMPLIFIED GEOMETRIES

F. Klunker[1], G. Ziegmann[1]

[1]Institute for Polymer Materials and Plastics Processing
Clausthal University of Technology, Agricolastrasse 6, 38678 Clausthal-Zellerfeld, Germany
and Corresponding Author's e-mail: florian.klunker@tu-clausthal.de

ABSTRACT: The Resin Transfer Moulding (RTM) process is a technology to produce fibre reinforced parts: fibres are placed in a mould and resin is injected into the closed mould, impregnating the fibres. After curing the resin the part will have more or less its final shape. In order to reduce the costs and time of engineering, a lot of work has been done to simulate this process. The equation most often used for simulating this process is Darcy's Law.

The simulation programs based on Darcy's Law are often using a finite element / control volume approach. This technique can be applied to nearly every kind of geometry with accurate results in a convenient time, but it requires the user to have experience in the RTM-process in order not to do too many simulation experiments by trial and error while trying to optimise the process parameters. In this publication a fast solution method is presented for modelling the RTM-process using simplified geometries, which is often applicable in manufacturing of RTM-parts. The resulting numerical technique is based on the theory for ordinary differential equations. It can be used for predicting the best injection zones due to time and dry spots caused by entrapped air as a result of flow fronts which are getting into contact without control.

KEYWORDS: RTM, analytical modelling, numerical analysis

INTRODUCTION

Fibre composites offer the opportunity to do light weight construction. Due to their anisotropic mechanical behavior it is possible to save up to 30% of the weight compared to metallic parts with the same properties. Some fields of applications are the automotive, nautive, aircraft and sports industry.

Another advantage is that complex shaped parts can be created with only a small amount of waste material. Several techniques to produce fibre reinforced parts [4] exist.

The Resin Transfer Molding (RTM) is one technique to produce fibre reinforced parts [4,6,9]. Dry fibres are inserted into a mould, resin is injected and after curing the final part can be demolded. The challenge of this technique is to

- inject the resin without remaining dry spots, meaning unimpregnated fibres,
- predict the appearing mold pressure to do a cost effective mold construction,
- reduce residual stresses due to shrinkage of the curing resin.

Those difficulties are caused by the design concept of the parts: the anisotropic property of the fibres causes a complex flow behavior. Simulation tools for simplifying the design process were developed [1,15]. In many cases a discrepancy between reality and experiment has been observed. In order to improve accuracy of the flow simulation there are several proposals to refine the modelling of the process [2,7,11,13].

The design process consists of several stages. First, the main idea has to be developed, after that the design is getting more and more detailed. While simulation is getting present in all construction stages, it would be helpful to see possible difficulties concerning the flow behavior in the early stage of the design. The usual way to do RTM simulation is to create a mesh from a given CAD-File, import it into the RTM software and apply process and material parameters. But during the design process often there are no valid geometries or some detailing ideas are missing, so that creating pre-final parts would increase the time of engineering.

In this paper a solution is presented to do RTM simulation mesh free. It can be applied in an early stage of the construction process by selecting “important” points. The formulation can be done with ordinary differential equations. The accuracy is of course lower than within the usual RTM-simulation, but due to the high performance, several possibilities for application are opened:

- automatic injection port and vent location proposals,
- cost and process analysis for feasability studies,
- automisation and real time control of the process,
- rough estimation of the rheological behavior taking into account the influence on void content.

THEORY OF THE FAST SOLUTION ALGORITHM

Governing Equations

The stationary flow through porous media is often modelled by Darcy’s Law [1-15]:

$$v = -\frac{K}{\mu} grad(p) \tag{1}$$

where v is the volume averaged velocity, K the permeability tensor, μ the resin viscosity and p the fluid pressure. If ρ describes the density of the resin, the continuity equation can be written as [11]

$$\frac{\partial \rho}{\partial t} + div(\rho v) = 0 \tag{2}$$

It is often assumed that the flow is at steady state [15], meaning that the time derivative is neglected, and the fluid is incompressible so that Eqn. 2 can be simplified. Using Darcy’s Law in Eqn. 2, the resulting equation is

$$div(\frac{K}{\mu} grad(p)) = 0 \tag{3}$$

This is an elliptic partial differential equation describing the pressure field of the impregnated region of the RTM process at one time step.

Fast Solution Algorithm

For a one dimensional problem, the solution for Eqn. 3 can be written as

$$P(x) = \frac{P_2 - P_1}{L} x + P_1 \tag{4}$$

where P_1 is the pressure at the injection port, P_2 the pressure at the vent and because of the low viscosity of the air it can be assumed that it is also the pressure of the flow front. L is the infiltrated length and $x \in [0, L]$ the position within the wet fibres.

For higher dimensional problems the solution is depending on the shape of the part. One possibility to solve this problem is by using the Finite Element Method (FEM). The advance of the flow front from timestep to timestep is often done by a so called Control Volume Method (CV). This technique is used by several authors [1,15] to simulate the process. With the combination of heat equation and curing those programs lead to a powerful tool for designing the processes. With special tools it can even be used for optimizing the process parameters [3,5,14].

When new parts are designed it is also required to fulfill the conditions of the production. With simulation it is possible to influence the design process before the first experiments are made. The fast solution algorithm offers the opportunity to investigate the flow behavior even without a final shape. It deals with one dimensional domains describing the flow and the geometry approximately. This is done by a set of nodes connected by one dimensional domains.

The node N_i of s nodes is given. From this nodes flow Q_{ij} of fluid to the nodes $N_j, j = 1,..,s$ are given. Because of the incompressibility of the resin, the remaining fluid Q_{ii} in node N_i is zero, meaning:

$$\sum_{j=1}^{s} \dot{Q}_{ij} = 0. \tag{5}$$

Because of the 1D-geometry of the domains, it can be assumed

$$\dot{Q}_{ij} = v_{ij} A_{ij} = A_{ij} \frac{K_{ij}}{\mu} \frac{P_i - P_j}{L_{ij}} := D_{ij}(P_i - P_j). \tag{6}$$

with v_{ij} the velocity of the flow front in the domain leading from node i to node j, $\dot{Q}_{ij}$ is the volume flux through cross section A_{ij}, K_{ij} the permeability and L_{ij} the length. With these definitions the pressure inside the domains can be calculated with

$$\sum_{j=1}^{s} \dot{Q}_{ij} = \sum_{j=1}^{s} D_{ij}(P_i - P_j) = 0. \tag{7}$$

Taking into account that L_{ij} is varying with domains which are partially filled, this can be used for calculating the progress of the flow front in the second step with Eqn.1. The theory needed for solving these equations is the theory about ordinary differential equations. For this kind of equations several numerical solvers are available [16].

APPLICATIONS

Prediction of Filling Time

With the fast solution algorithm it is possible to do rough simulations in fractions of a second. As an example a steering wheel is presented showing the quality of the algorithm.

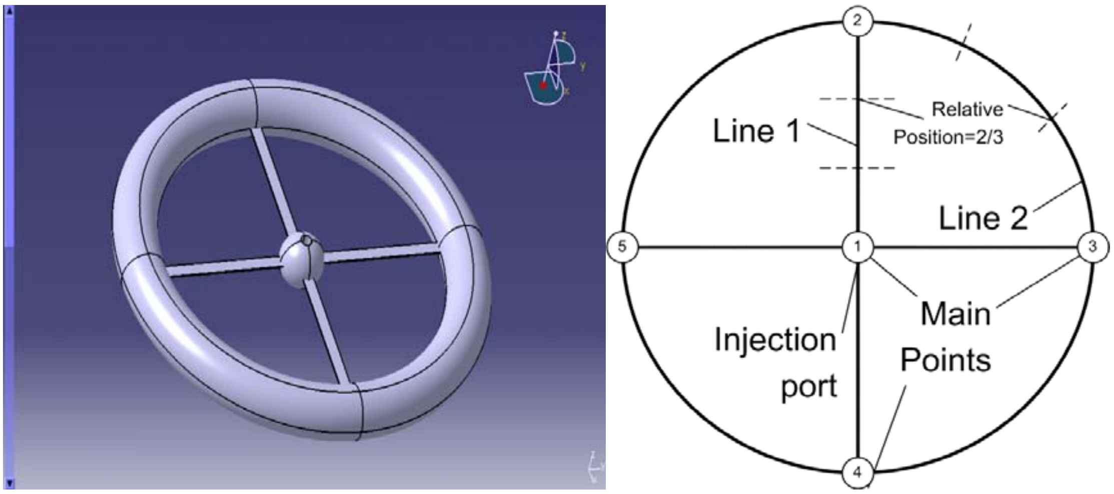

Figure 1: The complex model on the left can be simplified to a model which can be handled by the fast solution method.

A torus with 20mm radius and a diameter of 150mm is connected with a cross shaped structure having a cross section area of $0.01 \times 0.001 m^2$. In the center there is a sphere with a diameter of 40mm. This geometry is transferred to a one dimensional geometry as sketched in fig. 1. In the simulation an information about the area of their cross section of the lines is saved, so that the volume based formulation can be applied. The permeability is set to 10^{-11} m^2 for all lines and the viscosity is set to 0.1 mPas. The errors of calculation are expected to be at the sphere in the center and the connections at the outer ends of the crosses.
A simulation with PAM-RTM has been done leading to a simulated filling time of 356.000s. Using the fast solution algorithm, it leads to a simulated filling time of 335.100s which is an error of 5.8%. Using a simple step control technique to reduce the calculation time, the result was 357.472s which is an error of 0.4%.
This improvement is not caused by errors during the stepping process; it is just caused by the rough stop criterion which is cancelling the iteration process of reaching a filling factor of exactly one for every line after a few iterations.
In a second step, a similar geometry is used again: The cross in the middle has a bigger cross section: $0.02 \times 0.02 m^2$. The objective of this modification was to see a better result compared to the simulation in PAM-RTM because the relative part of a non 1D flow should be reduced. The filling time simulated with PAM-RTM is 11.364s. With the original shape and the fast solution algorithm it is 10155s, so resulting in an error of 11.9%. Using stepping techniques it is 10760s, so the error is reduced to 5.6%. This error is higher than in the first experiment. The reason for that behaviour has to be investigated in detail.

Proposals of Injection Points and Vent Locations

With the fast solution algorithm it is possible to predict the flow behaviour in the part as function of the injection position. Using the part in fig. 1 the injection positions are varied on the different connections between the main points. Due to the symmetric nature of the part, it has been done on line 1 and line 2. The results of the part with the thin cross are presented in the upper row of fig 2. The position of the injection port is simulated at 100 positions between the prior injection port having the relative position of zero and the connection of the torus and the cross with a relative position of one. The lines should be smooth but the filling time is dependent on the stop criterion.

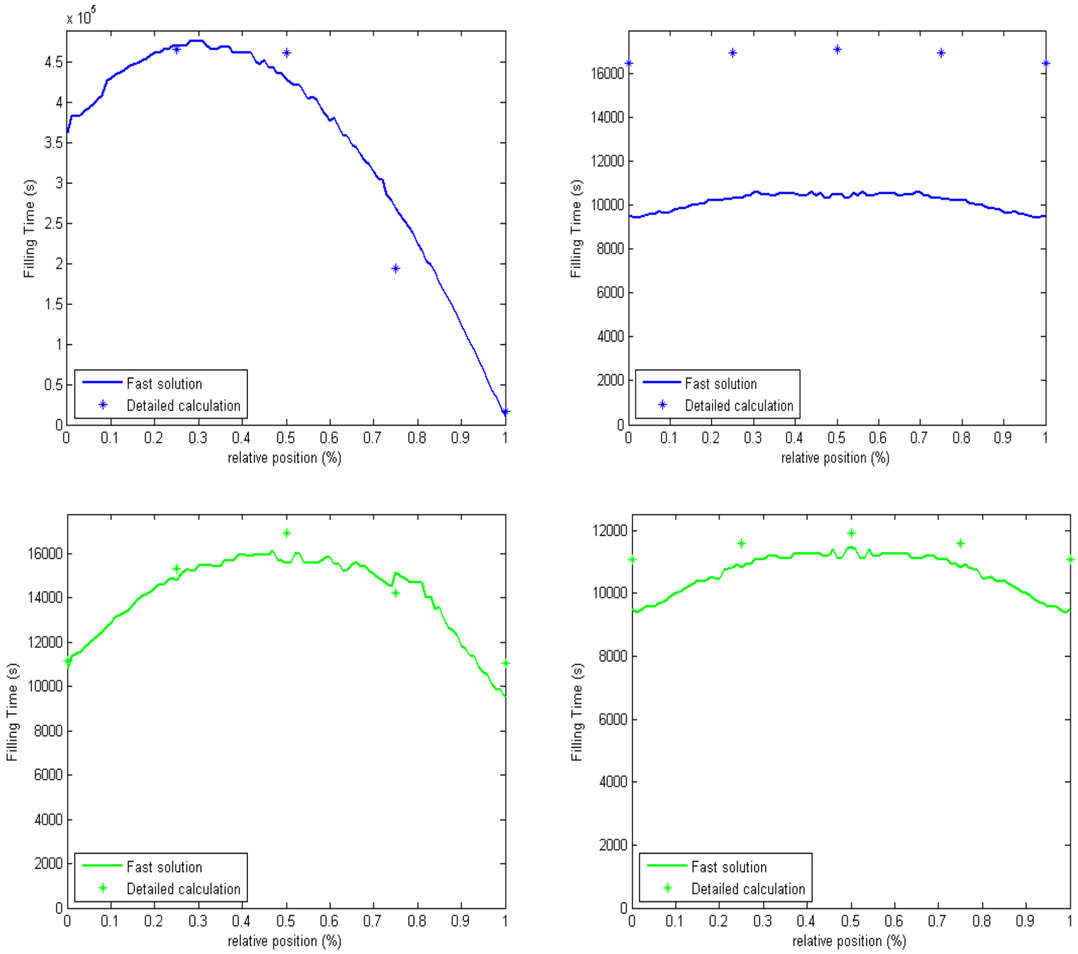

Figure 2: Results of the Filling Times when the injection port location is moving on Line 1 (left) and Line 2(right). The upper row represents the results for the thin cross.

It can be seen that the best injection port position on line 1 is at the relative position one which is equal to the main point 2 and the worst is close to the relative position of 1/3. The times differ with factor of about 35. Varying the position on line 2, the results are symmetric to the middle of the line. Here also 100 simulations have been done with the result that again the connection points of torus and cross is the best position.

Comparing these results with those of PAM-RTM it is shown again that the times are underestimated. The basic shape of the injection times can be seen. The accuracy of the filling times especially in the case of varying the injection port location on line two is low (relative error: about 80%). This is due to the missing model of the sphere in the middle. The time required to fill this sphere is approximately 4000 seconds. Subtracting that time the error is about 20%.

The results of the five 3D simulations with about 35000 elements were achieved after 4 hours. The results of the 200 one dimensional simulations were achieved after 2 minutes.

The simulation of the steering wheel with the thick cross was showing more accuracy while varying the injection point position: as it can be seen in the lower row of fig. 2 the relative error does not exceed 15% and the basic shape of the simulations run in PAM-RTM could also be reproduced.

LIMITATIONS

Due to the modelling with 1D-geometries the applicability of the fast solution method is limited. Some topics which cannot be represented should be explained.

VARI

One of the further developments of RTM is the Vacuum Assisted Resin Infusion (VARI). In this process, one part of the mould if substituted by a foil. Instead of using pressure to inject the resin into the mould, the resin is infused by applying vacuum at the outlet.
When this process is modelled, the deflection of the preform due to the lower compaction pressure because of the pressurized resin has to be taken into account. The pressure is a local variable influencing the permeability and so the solution on the whole domain. It seems possible to model such a behaviour with the volume based formulation, but the authors assume that the number of nodes have to be increased and in this case the advantage compared to FE/CV-techniques is decreased a lot.

2D and 3D flows of a general Shape

Describing multidimensional flows with the fast solution algorithm requires implementing handling rules. For general flow fronts this would decrease the computational performance.
For the case of radial or elliptical flow fronts which are for example present in cone shaped parts, the volume flux equation can also be written in the shape like Eqn. (7). As an example the solution for Eqn. (3) in case of a point injection into an isotropic media is

$$P(r) = P_1 + (P_2 - P_1)\frac{\ln(r/r_0)}{\ln(r_f/r_0)}, r_0, r_f > 0, r \in [r_0, r_f]. \tag{8}$$

In Eqn. (8) r_0, r_f are the radiuses of the injection point and the flow front. When this expression is deviated and used it in Eqn. (7), the standard form can be received:

$$\dot{Q}_{ij} = v_{ij}A_{ij} = A_{ij}\frac{K_{ij}}{\mu}\frac{P_2 - P_1}{\ln\left(\frac{r_f}{r_0}\right)}\frac{1}{r} := \tilde{D}(P_2 - P_1). \tag{9}$$

Heat Conduction and Resin Cure

The temperature is a local variable often depending on position and time. A one dimensional formulation is often not accurate. The resulting temperature depends on the material properties, having an influence on the curing of the resin. This leads to the same problem as it is described in section for VARI. The fast solution algorithm can be used for isothermal processes or for checking the possible limits of the parameters used in a detailed model. So it can support a decision if a simulation with heat conductivity is necessary.

POSSIBLE FUTURE APPLICATIONS

It has been shown that the described procedure can reproduce the behavior of the filling times. In general it cannot produce results with the accuracy of the standard FE/CV codes, but it support the user finding strategies for a given process.

Cost analysis for feasability Studies

In a cost analysis process the filling time is an important parameter for the feasibility of a process. The filling time has an influence on the number of parts which can be produced, so also for the number of tools which have to be ordered. It also has an influence on the curing behavior which can be estimated in advance for selecting special resins.

Automation and Real Time Control of the Process

Uncontrolled flow can decrease the sucess rates of RTM-parts [3]. The control of processes often requires transient formulations and reference functions. In general, an exact model of the process is not required because the actuator should be changed in every time step. Due to the fast solution got, it is possible to calculate flow front information quickly. This can be used for opening vents and injection ports to influence the flow.

Rough estimation of the rheologic Behavior

Void contents decrease the mechanical performance of fibre reinforced parts. Several authors indicated that the balance of capillary number and permeability has an influence on the void content [10,12]. In conclusion to that some authors found out that the void content is dependant on the direction of impregnation [11].
There are already models existing handling formation of void contents. At our institute similar models were also developed, showing that the amount of macro and micro void content is dependent on the velocity of the flow front. The detection of regions containing voids is dependent on the size of the elements. With the fast solution algorithm and parameter studies at simple parts it is possible to propose a mesh sizing so that a proper mesh can be built.

CONCLUSION

A fast solution algorithm has been developed. It is a volume based formulation and it can be used for one dimensional flows. The applicability has been shown at a complex part. A general applicability is not yet given. The future work is to generalize the model without a loss of performance. The limits of applicability have to be formulated, so that standard applications have decision rules of applicability.

REFERENCES

[1] M. Bruschke and S. G. Advani, “A finite element/control volume approach to mold filling in anisotropic porous media”, *Polymer Composites*, Volume 11, Pages 398–405 (1990).

[2] M. Deleglise, C. Binetruy, and P. Krawczak, “Solution to filling time prediction issues for constant pressure driven injection in RTM”. *Composites Part A: Applied Science and Manufacturing*, Volume 36, Pages 339– 344 (2005).

[3] M. Devillard, K. T. Hsiao, and S. G, Advani, “Flow sensing and control strategies to address race-tracking disturbances in resin transfer molding - Part II: automation and validation”, *Composites Part A: Applied Science and Manufacturing*, Volume 36, pages 1581–1589 (2005).

[4] M. Flemming, G. Ziegmann, and S. Roth, “Faserverbundbauweisen“, Springer, Berlin (1999).

[5] J. Gou, C. Zhang, Z. Liang, W. Ben, and J. Simpson, „Resin transfer molding process optimization using numerical simulation and design of experiments approach” *Polymer Composites,* Volume 24, Pages 1–12 (2003).

[6] U. Huber, “Zur methodischen Anwendung der Simulation der Harzinjektionsverfahren“, Dissertation, Kaiserslautern (2002).

[7] B. Joel, Y. Henzel, F. Trochu, and R. Gauvin. Analysis of dynamic flows through porous media. Part I: Comparison between saturated and unsaturated flows in fibrous reinforcements. *Polymer Composites*, Volume 24, Pages 391–408 (2003).

[8] P. Knaber and L. Angermann, „Numerik partieller Differentialgleichungen - eine anwendungsorientierte Einführung“, Springer, Berlin, Heidelberg, New York (2000).

[9] M. Louis, „Zur Simulation der Prozesskette von Harzinjektionsverfahren“, Dissertation, Kaiserslautern (2004).

[10] T. Lundström, “Bubble transport through constricted capillary tubes with application to resin transfer moulding”, *Polymer Composites*, Volume 17, Pages 770–779 (1996).

[11] B. Markicevic, D. Heider, S.G. Advani, and S. Walsh, “Stochastic modeling of preform heterogeneity to address dry spots formation in the vartm process”, *Composites Part A: Applied Science and Manufacturing*, Volume 36, Pages 851–858 (2005).

[12] N. Patel and L. James Lee, “Modeling of void formation and removal in liquid composite molding. Part II: Model development and implementation”. *Polymer Composites*, Volume 17, Pages 104–114 (1996).

[13] K. Pillai and S.G. Advani “Numerical simulation of unsaturated flow in woven fiber preforms during the resin transfer molding process”, *Polymer Composites*, Volume 19 Pages 71–80 (1998).

[14] E. Ruiz and F. Trochu, “Comprehensive thermal optimization of liquid composite molding to reduce cycle time and processing stresses”, *Polymer Composites*, Volume 26, Pages 209–230 (2005)

[15] X. Song, “Vacuum Assisted Resin Transfer Molding (VARTM): Model Development and Verification”, PhD thesis, Virginia, 2003.

[16] E. Hairer and G. Wanner, “Solving Ordinary Differential Equations 1. Nonstiff Problems”, Springer, Berlin, Heidelberg, New York, 2000.