

Skills Synergy Leading to RTM Flow Simulation Success Story

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ABSTRACT

Industrial requirements imply optimising the development cycle, reducing manufacturing costs and reaching marketable product maturity as fast as possible. The design stage often involves multiple sites and various partners. In this context, the use of computer simulation becomes absolutely necessary to meet industrial needs. Nevertheless, this activity can be effective only if it is integrated correctly in the industrial organisation. In the aeronautical and space systems industry, mechanical specifications often require the use of composites reinforced by continuous carbon fibres. The goal of this article is to describe how, on a time frame of nearly twenty years, a series of scientific and technical tasks were carried out in partnership in order to develop, validate and implement Resin Transfer Moulding (RTM) flow simulation and cure analysis for high performance composites. The research stage started at the university in 1991. Nearly at the same time, a first commercial venture by a spinoff company offered the software to a limited number of users, all involved in the joint development of new resin injection technology for

composites. In the end, after involving in 2001 an international software editor in the technology transfer, efficient process simulation computer tools were integrated in the industrial working environment. This kind of technology transfer was achieved through a unique collaboration between EADS France IW, an academic research team at École Polytechnique de Montréal (EPM) and a software editor, ESI Group. A new methodology including permeability measurements and resin kinetics experimental characterisation was devised, validated and applied to EADS composite parts. A new version of the RTM process simulation software has been fully integrated in 2006 by ESI Group and AIRBUS S.A.S. in CATIA V5 computer aided design environment. More recently, a parallel version appeared in 2010 to solve flow problems in large parts.

INTRODUCTION

Since the beginning of the 1990s, École Polytechnique de Montréal (EPM) has developed a new approach for the numerical simulation of mould filling in Resin Transfer

Moulding (RTM). The first version of the code was a Unix based finite element software called RTMFLOT. The first industrial user of RTMFLOT was Société Nationale Industrielle Aérospatiale (SNIAS) in 1993 through the “Centre Commun de Recherches Louis-Blériot”, Suresnes, France, followed shortly by Ford Research (Detroit) and Snecma (Paris). The first academic users were LGMT in Toulouse, ETH in Zurich and École Polytechnique de Nantes. RTMFLOT software included already 3D finite element analysis and non isothermal flow simulations of mould filling and cure. One original feature of RTMFLOT consists of using a non conforming finite element approximation of Darcy's flow. This enables proper simulation of race tracking (also called “edge effects”) without having to refine unduly the finite element mesh in the vicinity of preferential flow channels. The software allows an accurate conservation of the resin mass during mould filling.

Around 1995 limitations of the RTM process clearly appeared in the manufacture of composites by resin injection, especially for large parts of high fibre volume content. In order to simulate emerging flexible injection processes regrouped under the generic name of Liquid Composite Moulding (LCM), it was necessary to rewrite entirely the code. The new computer program was called LCMFLOT. Instead of simulating only resin injection in rigid moulds like RTMFLOT, LCMFLOT had the capability of analysing flows in deformable moulds, in which permeability, porosity and preform thickness vary in time during resin injection. Resin infusion, injection-compression, RTM-Light are examples of such LCM flexible injection processes. The new LCMFLOT code was also developed in a Windows environment, which reduced the cost of the computers required to use the software. Finally, it was interfaced with other major software codes in use in the field of composites such as Patran and FiberSim. When it was transferred to ESI Group in 2001, LCMFLOT had around 30 academic and industrial users.

Technology transfer from university to industry requires time, dedication and a close collaboration between partners. Academic researchers are not always fully aware of the time required to go from a product ready at the research level to an industrial tool for end users. Most of the time the effort necessary to industrialize a product, process or software is as long and important, if not more, than the scientific development of the new technology. This paper gives an account of the success story and exemplary collaboration between a university (École Polytechnique de Montréal), a leading aerospace company (EADS) and a software editor (ESI Group) that led to the development of the commercial flow and cure analysis code PAM-RTM. This comprehensive scientific software devised to simulate Resin Transfer Moulding (RTM) was developed, validated and brought to market by the concurrent work the above three partners. The work carried out can be divided in three parts:

1. The first part describes the main features of the numerical method developed at EPM to simulate the RTM process. The equations of Darcy's boundary value problem are presented together with the methodology followed to move the flow front during mould filling. The advantages of using a non conforming finite element approximation of the pressure field in the mould are outlined, because it ensures an accurate conservation of the resin mass in the mould during the numerical calculations.
2. The second part addresses the issues of experimental validation and integration of process simulation in an industrial composites tool design and fabrication loop. The work was carried out by EADS IW (EADS IW) with the assistance of EPM. It included the development of a new permeability measurement technique based on the methodology published in 1996 [1] and further refined [2].
3. Finally, the third part describes the contribution of the software editor, ESI Group. In order to integrate PAM-RTM [3] in the CATIA V5 working environment of AIRBUS S.A.S., a close collaboration between EADS IW and ESI Group was required.

PART I. DEVELOPMENT OF A NUMERICAL SOLUTION FOR RTM PROCESS SIMULATION

The numerical method used in PAM-RTM was published in 1993 by Trochu et al. [4]. The equations of Darcy's transient boundary value problem and the filling algorithm are first presented, followed by a description of the fill factors on a fixed mesh and a discussion on the numerical method. The main reason why non conforming finite elements were chosen lies in their ability to ensure a strict conservation of the fluid mass across the inter-element boundaries. In order to illustrate these ideas, a linear non conforming finite element is constructed in [Figure 3](#) on a triangle.

DARCY'S BOUNDARY VALUE PROBLEM

The resin impregnation is usually modelled as a flow through a porous medium. It is governed by Darcy's law, i.e., the directional flow rate vector $\mathbf{q}$ per unit area, also called Darcy's velocity, is proportional to the pressure gradient

$$\mathbf{q} = -\frac{\mathbf{K}}{\mu} \nabla p \quad (1)$$

where $\mathbf{K}$ is the permeability tensor (m^2), p the resin pressure (kPa) and μ the fluid viscosity (Pa.s) assumed constant for a Newtonian resin. Combining (1) with the continuity equation $\nabla \cdot \mathbf{q} = 0$ gives

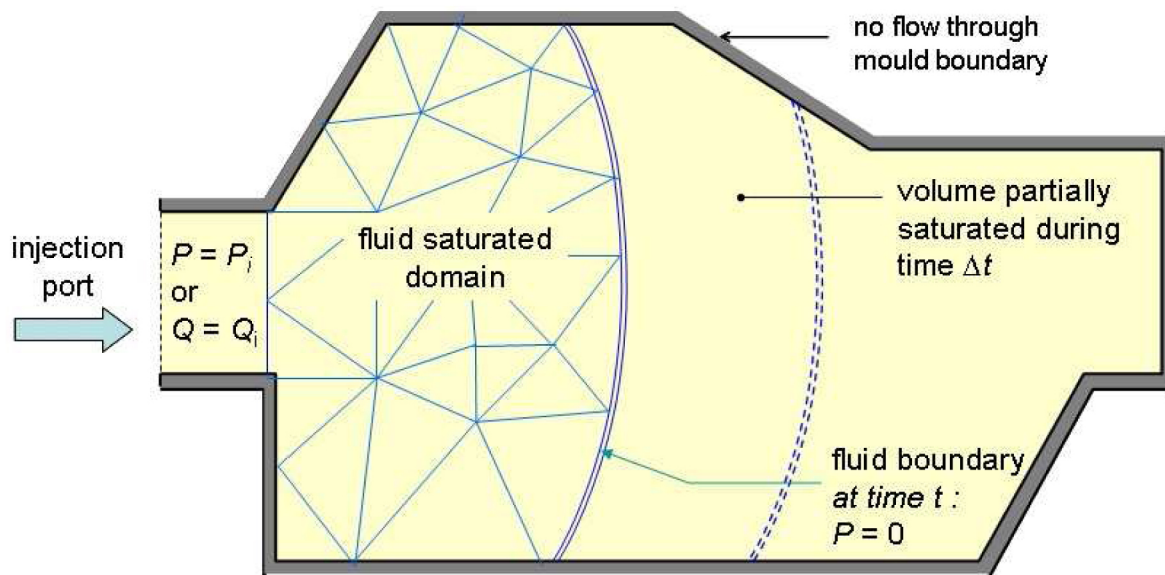


Figure 1. Schematic of the saturated domain in which Darcy's boundary value problem is solved.

$$\nabla \cdot \left(\frac{K}{\mu} \nabla p \right) = 0 \quad (2)$$

Equation (2) is solved at each time step inside the saturated part of the mould using non-conforming finite elements. Figure 1 gives a schematic view of the boundary value problem governed by equation (2) at any given time during mould filling. The usual boundary conditions are either of constant pressure $P = P_i$ or constant flow rate $Q = Q_i$ at the injection port. However, transient boundary conditions can also easily be considered. On the resin front, the pressure is constant at zero ($P = 0$). Along the impermeable mould walls, the normal derivative of pressure vanishes, since there is no resin flow through the mould wall. The resin pressure distribution is obtained by solving Darcy's equation at each time step inside the saturated part of the mould. Then the velocity is computed on the resin front from the pressure field, thus yielding the flow rate across the resin front. At each time step, an increasing number of elements in the mesh become saturated and a new position of the resin front is determined, from which the simulation can proceed for a new iteration.

FILLING ALGORITHM

The numerical treatment of the transient free surface or moving boundary plays an important role in the simulation of mould filling processes. The resin entering inside the mould is constantly changing shape as it flows, so the geometry of the saturated domain must be redefined several times during the analysis. Two different types of numerical procedures can be employed to simulate an injection process: *moving grid* techniques such as the boundary fitted finite difference

method of Coulter and Guçeri [5] or Li and Gauvin [6], in which the resin saturated part of the mould is remeshed at each time step; and *fixed mesh* approximations, in which the progression of the resin front is followed during mould filling by a fill factor associated to each element of the mesh. As pointed out by Gauvin and Trochu [7], the first family of numerical techniques is not only very time consuming, but it cannot also be easily implemented in moulds of complex shapes with inserts or multiple injection ports. On the other hand, fixed meshes, together with a control volume approximation of equation (2), have been used by many investigators such as Bruschke and Advani [8] or Young et al. [9]. The method of Trochu et al. [4] programmed in LCMFLOT follows also a fixed mesh approach, but instead of being associated to each node of the mesh, the control volumes are simply the elements of the mesh. This makes the numerical procedure simpler and faster, because no control volume needs be constructed around the nodes of the finite element mesh (which can be tricky for 3D analyses). In fact, each element of the mesh is a control volume, in which the balance of incoming and outgoing flows is calculated to approximate Darcy's problem (2).

Fill Factors

The geometric domain representing the saturated part of the mould at each calculation step is decomposed into a finite number of triangular slices as shown in Figure 1. Triangular elements are preferred over quadrilaterals, because they better approximate irregular shapes. These elements are also simpler to utilize with a linear interpolation than quadrilaterals, which involve a second degree term. This speeds up the computation of the finite element elementary matrices. Each solid element may have a different thickness. The program takes into account the exact volume of the