COMPUTATIONAL BENCHMARK DEFINITION FOR LIQUID COMPOSITE MOULDING PROCESSES

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SUMMARY

This paper proposes a new mathematical definition for the optimal flow behavior in LCM processes. It is based on a class of homothopy maps and the use of Flow Pattern Configuration Spaces in order to characterize an idealized mould filling process. In a previous work [12], [17], is proposed the use of configuration spaces for the computational treatment on LCM process design tasks, permitting to define the mould in an alternative space represented by configuration variables. In [12], the distance to an interest process point or multiple points like pipes is used as configuration variables where the resulting space is called Flow Pattern Distance Space (FPDS). It permits to represent whatever mould dimension in 2D (FPDS-2D) or 1D (FPDS-1D) space allowing solving LCM problems in a simplest manner than in Cartesian representation. Through these spaces, it is easy to solve the optimal pipe location for the optimal mould filling, [13]. In the present work are used this spaces to define which is the optimal flow front shape in each time instant. For instance, for a Resin infusion process where the outlet is usually located in the mould contour, the optimal flow behavior is a continuous deformation of the outlet to the inlet. Using a FPDS-1D, just only is necessary to deform the contour represented by a mono-dimensional curve. The use of the FPDS-1D permits to formulae the optimal flow behavior in a mono-dimensional equation, independently on the mould dimension. At the end of the paper are shown experimental results to demonstrate that the flow has this behavior when pipe resolution is increased as in [12].

Keywords: Homothopy maps, optimization techniques, Flow Pattern Configuration Spaces, pipe

INTRODUCTION

Resin infusion process is one of the common techniques used in the industry for large composite parts production. This technique uses vacuum pressure to drive the resin into a laminate. Perform is laid dry into the mould and the vacuum is applied before the resin is introduced. Once a complete vacuum is achieved, resin is sucked into the laminate via placed tubing. This negative pressure allows the top half of the mould to be made of a flexible material, thus reducing costs permitting manufacturing parts of practically any size, see Figure 1.

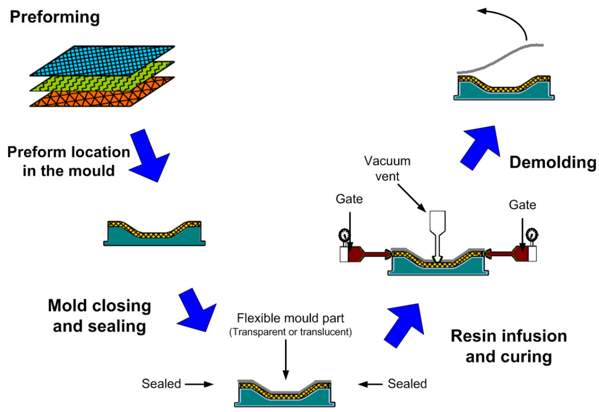

Figure 1 Resin Infusion Process stages

The top half of the mould is usually a bagging film, allowing introducing distribution channels like pipes to improve the filling process [1], [2]. These channels can be taking whatever shape, introducing a new degree of freedom in the RI process design. In this sense, optimization tools must be developed to find which the optimal one for each case is. In the literature, there are an amount of works that treats to optimize the filling process but for RTM processes [3],[4],[5],[6],[7],[8],[9]. In this case, the inlet and the outlet are discrete points that are more simple case than search a shape and the dimension of an optimal channel distribution. In RTM optimization works a common technique is to use a FE simulation coupled with genetic algorithms. A genetic algorithm, in general, has a better chance to locate the near global optimum especially in problems with multiple variables and a large search space. The disadvantage is that the calculation time of 600 generations with a population size of 30 on a 448 element model was over 75 hours [3]. Therefore, researches works into reduce the computational cost but maintaining the same structure, FE simulation coupled with genetic algorithms. In [9] is proposed a branch and bound search to improve the genetic algorithm. In [6], [7] is proposed the use of neuronal networks to improve the computational simulation costs. Through this works, the computational costs is reduced to minutes instead hours for RTM process. In [8] is also used a genetic algorithm to optimize the inlet and outlet but replacing the flow simulation for the mesh distance based approach.

In [1], [2] are proposed the first and, to authors knowledge, the unique works that threats to solve the optimization problem for RI processes. In [2] uses RTM software and a genetic algorithms to find the optimum for the diameter of the flow runner channel and the amount of layers of a flow distribution medium. In this work, the position of the flow pipes and distribution medium were fixed and determined by the user in advance. In [1], a mesh distance based approach proposed in [8], coupled to a genetic algorithm is used to find the flow pipe position. As the flow pipe is not a point, the distance of each node to the pipe is the minimum distance to the pipe nodes to each node. Although this work presents some interesting improvements, also have important limitations. The first one is also the excessive calculation time. The optimal solution of a rectangular mould was reached after 17 minutes on a 2.01 Ghz PC. The second limitation is that considers the vents as points, not vent pipes allocated in the mould contour. This issue increase one of the disadvantages that the use of a vacuum bag has in Resin Infusion processes, that is, the local pressure gradient may be different in each mould zone. It implies that different thickness zones can be occurred and then different permeability zones. To minimize this effect, the vent is usually located in the mould contour, and then the optimization algorithm must be taking it into account.

All of this optimization tools has an objective function that measure the quality of this solution. This objective functions are based on LCM process parameters like, minimum filling time, dry spot prevention, homogenized curing, flow front velocity, etc. These numerical indicators are well known in LCM processes as process performance index (PPI). In [10] is developed an index based on the minimum filling time and a vent-oriented flow front. At a given step, the distances from the nodes located on the resin flow front to the outlet are associated with the quality of the filling process. The standard deviation of those distances is used to evaluate the shape of the flow front (The lower the better). The reason of the distance measurement is because produces a dry spot prevention in the filling stage. The second term is the total filling time, measuring the mould productivity. This PPI index is improved in [11], taken into account the differences in the incubation time values of all the nodes impregnated by the resin. In **¡Error! No se encuentra el origen de la referencia.** is showed a state of the art of optimization algorithms. As a conclusion, optimization tools in LCM processes must be improving to reduce computational costs. In addition, for RI processes where the inlet can be complex shapes, the problem becomes more complex than RTM process, where the inlet and the outlet are points. For this propose, in our previous work, [12], is proposed a new concept to compute optimization or control algorithms in LCM processes, and called Flow Pattern Configuration Spaces (FPCS). The main interesting idea of using these spaces is the definition of the coordinate system by means of the process parameters related to the flow, instead of a customary Cartesian coordinate system. These spaces are commonly used in mobile robots using as parameters, wheeled turning radius, path length, velocity etc. It permits to improve the understanding of the process and inherently reducing the computational costs in the decision tasks. In these spaces, a mould mesh discretization is defined using an alternative coordinate system. One of this coordinates is based on the radial flow behavior. Hence, the angle defined by an interest point, such is the nozzle injection or the vacuum vent, to the evaluated point location is selected as a fixed parameter of the FPCS. The other parameter is liberated to be selected, and depends on the application of the FPCS. In this sense, one of the configuration spaces proposed in [12] uses as free parameter the node to node mesh distance. This distance is used in some works not only to replace the simulation, [1], [8], also to measure the proper filling process [10],[11]. The resulting space is called *Flow Pattern Distance Spaces* (FPDS). For 2D moulds, this distance is computed with the Euclidean distance but, for 2.5D moulds it is used the geodesic distance. Through this distance and the angle defined by the interest point, it is possible to develop two kinds of spaces, called FPDS-2D, FPDS-1D. Next figure shows a resume of the FPDS construction.

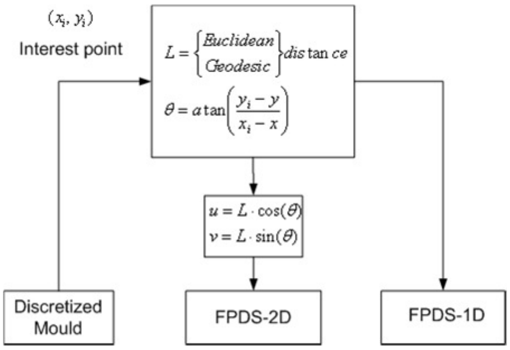

Figure 2 Flow Pattern Distance Space construction

In Figure 3 are shown two examples for the FPDS, one for a 2D square mould, and other for a complex 2.5D mould. The point transformation is the centroid or mass centre. In this examples, a simulation in the Cartesian space selecting the interest point as a constant pressure inlet (1 bar), is show in the resulting FPDS mesh.

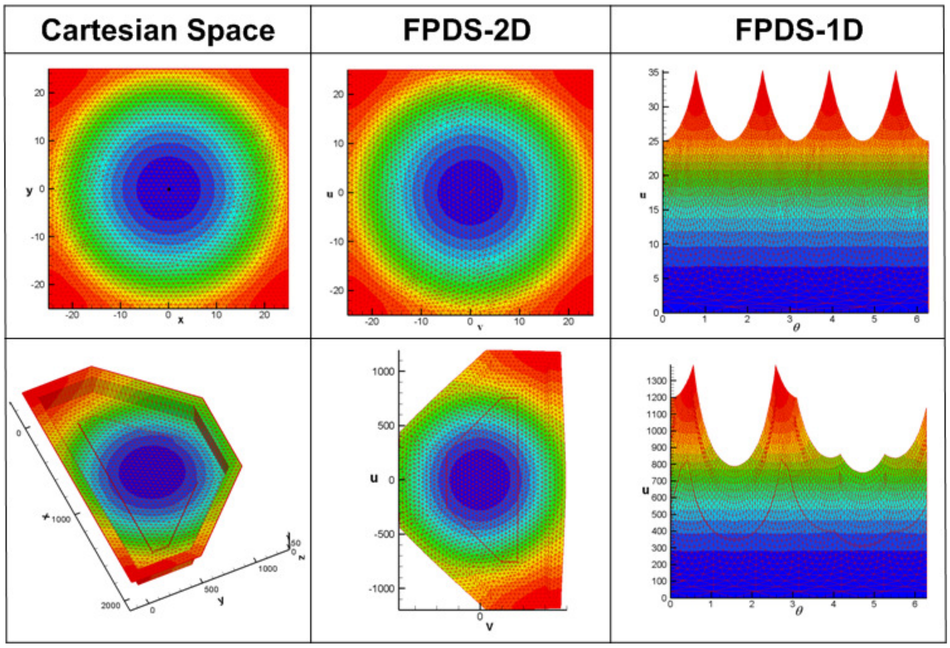

Figure 3 Examples of the FPDS transformation

These spaces are connected through the mould nodes, [12], making possible to translate the computations developed in these spaces to the Cartesian space. The main advantage of use these spaces, instead of Cartesian spaces is that, they are developed using a LCM parameter to optimize or to control, in this case, node to node distance. It produces a reduction in the dimension of the problem, making different an algorithm proposed for a complex 2.5D geometry than for a 2D geometry where the coordinates are the variables to optimize or to control.

OPTIMAL INLET PIPE SHAPE AND ALLOCATION

The common algorithm used in the literature uses a simulation coupled with a genetic algorithm, see **¡Error! No se encuentra el origen de la referencia.**, where the

computational costs goes since 30 minutes to hours, depending on the mould complexity. In our previous work, [13], was presented an optimization algorithm for a Resin Infusion process, using a FPDS, obtaining an optimal inlet shape and allocation in less than one minute for whatever mould complexity and dimension.
In RI process, the vent is usually allocated in the contour mould to homogenize pressure distribution, and then minimizing different permeability zones. Then, the optimization algorithm must find the gate shape and the allocation of a pipe to achieve two main goals; the flow must reach the vent contour nodes at the same time instant in less time as possible. This criterions are the same than the used in the PPI index [10],[11]. In these cases, the flow front distance to the vent must be the same in each time instant to obtain an optimal filling process. It produces a dry spot reduction during filling but also guarantees that, at the end of the filling process, the flow achieves the vent at the same time. Therefore, as the inlet shape can be considered as the flow front in the initial time instant, the inlet shape and allocation must be the same distance to the vent. In addition, this distance must be as less as possible to minimize the filling time. If we try to develop an algorithm to find the shape and allocation of an inlet in a complex 2.5D mould, the algorithm can be complex where the logical solution is the common used in the literature. Contrary to this, if we try to develop an algorithm to solve the same problem in a FPDS-2D of a complex 2.5D mould, the problem becomes a geometrical problem, [13]. Therefore, the goal is to find a shape or a set of points that has equal distance to the contour. In [13] was proposed a Delaunay triangulation, see Figure 4 (left). The circle centre joined with the contour nodes gives the Voronoi diagram. Using this technique in the FPDS-2D, it is possible to determine the circle centers that are tangent with at least three contour nodes. These circles are called "*Bi-tangent circles*". The resulting curve is called main branch. It has the particular property that accumulates the points that has equal distance with at least three contour nodes where the radio measures the each gate effectiveness to the contour. Clearly, in a general case, this radios are different for each centre. In order to force equal radios, a secondary branch concept is introduced in [13] for the gate shape solution, see Figure 4 (right).

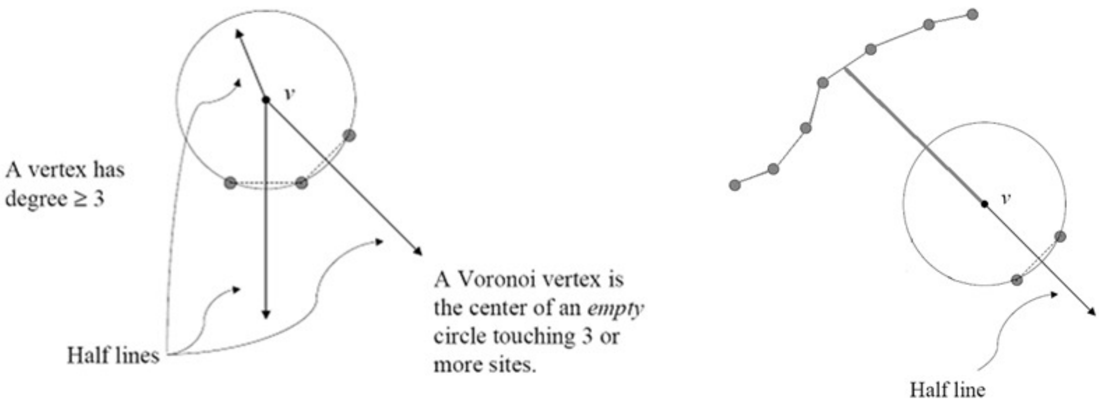

Figure 4 Main branch computation (left). Secondary branch (right).

Each single secondary branch guarantees that through the centre, has the same distance with at least two contour nodes. The half line of this contour nodes intersect with a line that joins two main branch points. Therefore, a single secondary branch is defined since the circle centre to the main branch point connection. The radio and the centre of each secondary branch can be changed, permitting to select the radio of the circle. Then, selecting a particular radio of the main branch, all the secondary branches have the same contour effectiveness. The number of secondary branches depends on the number of contour nodes. In order to reduce this excessive number, in the circle of each secondary branch, cannot be allocated another secondary branch, guaranteeing the maximum secondary branch effectiveness. At the end, a set of solutions can be found, depending on the main branch radio selection. When this radio is low, the pipe complexity increases but the filing time is reduced and the inlet/outlet distance becomes more homogeneous, allowing to obtain a proper mould filling processes.

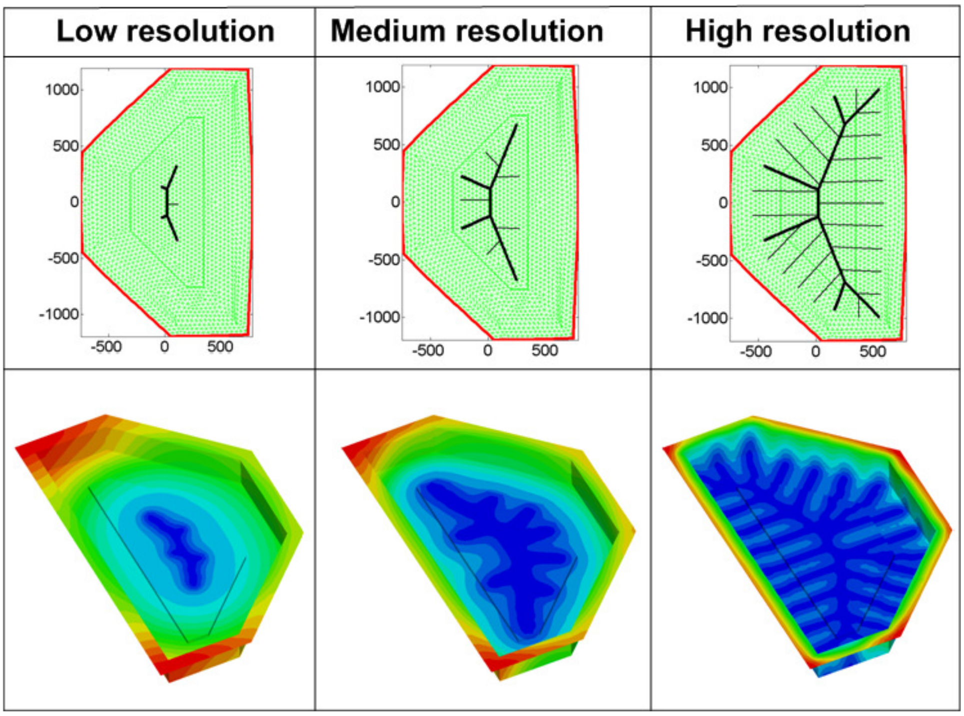

Figure 5 Example of the optimal inlet shape and allocation for a complex 2.5D mould

In Figure 5 (up) shows an example of the solution for different radios of the main branch. In Figure 5 (down) is showing the simulation results of the proposed solution. This simulation is developed selecting each nearest node as a single inlet pressure (1 bar). This approximation is possible selecting the channels as pipes because the flow runs to them around 1000 times faster than in the perform, [1], [13].

OPTIMAL FLOW BEHAVIOUR DEFINITION

In [10],[11] are stabilised numerical index to measure the proper filling process based on the criterions; *filling time*: The lower the better, *incubation time*: The lower dispersion in all the mould, the better and *flow front distance to the vent*: The lower distance dispersion, the better. From all of these criterions, the distance criterion imposes which is the optimal flow front shape in each time instant, avoiding dry spot formation. The resulting flow front shape is contrary to the natural flow evolution, radial from the inlet point, not to the vent. This natural flow evolution is the criterion used in some LCM optimization work [1], [8]. Therefore, it is possible to define the next concepts;

- Optimal filling process sees form the vent: *"A filling process, sees form the vent, must be radial to them"*

- Optimal filling process sees form the gate: *"A filling process, sees form the inlet, has a radial behavior to them"*

Both concepts are contrary but, at the same time are true or desirable. Then, it is necessary to redefine the optimal flow front shape in each time instant as;

"An optimal flow front shape are a continuous deformation from the filling sees form the inlet to the filling sees towards the outlet"

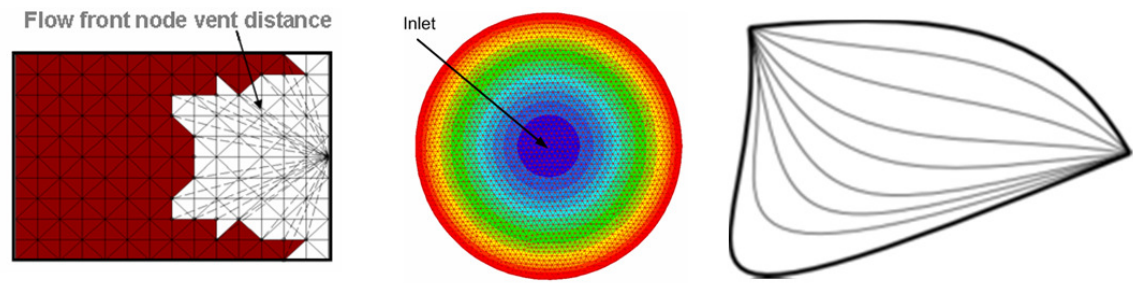

Figure 6 Flow sees from the outlet (left), inlet (centre), and homothopical (right)

This continuous deformation is known between mathematicians as Homothopy. Given two continuous functions in a topological space are said homothopical (greek=same and topos=place) is one of them can be "*continuous deformed* "to the other. Therefore, an optimal flow front between mould contour, φ^*, and the inlet, γ_0, can be formulated as $\mathrm{H}(\varphi^*, \gamma_0) = \varphi^* t_H + \gamma_0 (1 - t_H)$ between both curves where $t_H \in [0,1]$. This concept is extensively used in other fields like 3D animations. In these cases, continuous functions are parametric curves or surfaces like Bezier, B-Splines or NURBS, [14]. Also it is possible to use this concept to meshed objects, [15]. In these cases, it is necessary to define each node mesh path that must be following since the initial to the goal position. These paths are called *isolines*. The applications of this concept in LCM process are complex if it is sees in the Cartesian space but, if the application of this concept in the FPDS-1D is straightforward. Since this space, the contour (vent in RI processes) is a mono dimensional curve and the inlet (pipes) are a straight line allocated in the origin of coordinates. Then, both concepts, using parametric curve as a contour or using the relationship between the contour geodesics and the geodesics of each mesh node can be used for this propose. In this case we use the geodesics to compute it. Then, given a mesh node *n*, a relationship between the node distance to the origin, d_n, and the contour *isoline* that cross node *n*, d_{iso}, it is straightforward to compute the normalized time at which the flow front must be achieve to this node $t_H = d_n / d_{iso}$, where $t_H \in [0,1]$, see Figure 7.

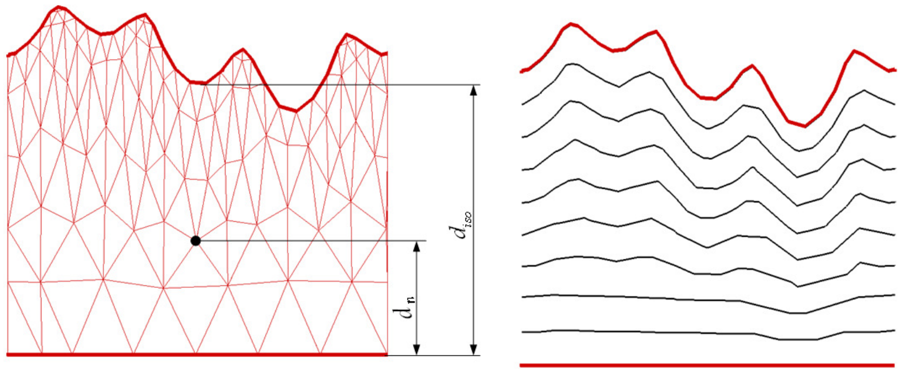

Figure 7 Homotophycal map computation through FPDS-1D

As a result, the optimal flow front shapes are defined in a class of "*Homothopy map*". In Figure 8 are shown examples of the homothopycal flow behaviour, using different optimal pipe resolutions. As can we show, when the resolution is increased, the flow evolution is closed to be homothopical.

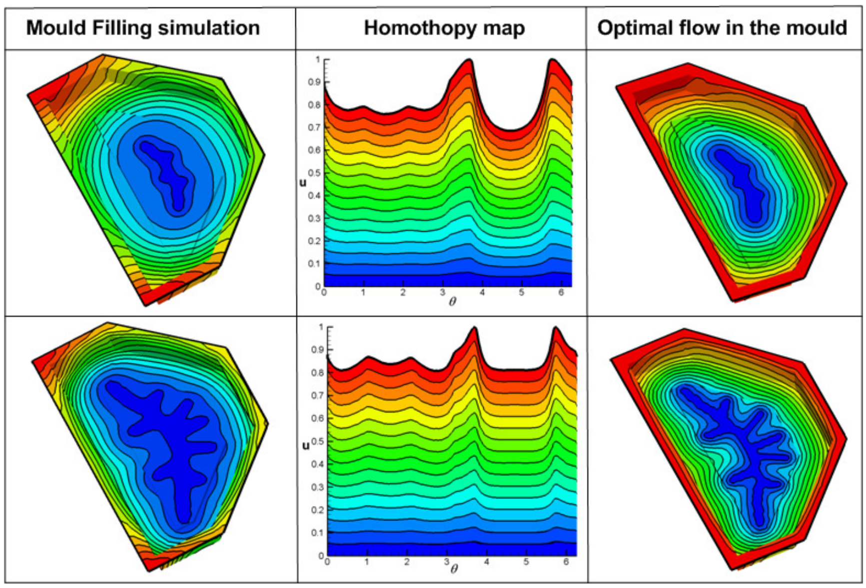

Figure 8 Optimal flow compared with the simulated flow using the optimal pipe

EXPERIMENTAL VALIDATION

In order to test this optimal behaviour an experimental installation presented in our previous work is used, [16]. It is based in a visible camera, thermal camera (infrared camera), projector and a laser. All of these devices must be calibrated previously to sense the same mould. This artificial vision pack allows obtaining a mesh to obtain the optimal pipe shape and allocation using the methodology proposed in [12]. After of this, the optimal result is projected to the mould to indicate the correct mould position. Figure 9 shows the flow behaviour for three examples, a square mould and a swimming pool. The square mould is tested using the main branch and adding secondary branchs. Swimming pool is tested with the main branch, [13].

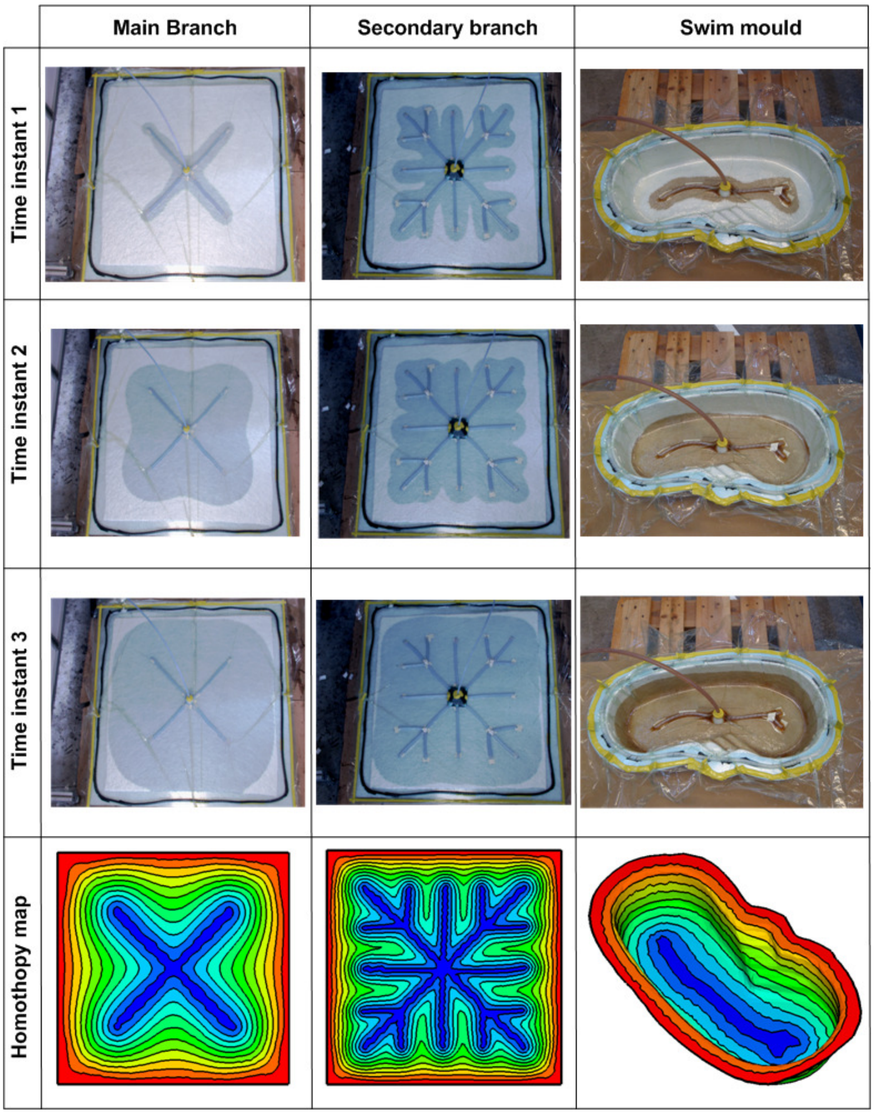

Figure 9 Experimental validation

CONCLUSIONS

In this paper is presented a mathematical definition of optimal flow front behaviour. It is based on a continuous deformation from the natural flow evolution, radial to the inlet, since the expected flow sees since the vent, radial to them. This continuous deformation is known as a homothopy and allows to define a homothopycal flow front map, given a predetermined inlet shape. In this paper, we demonstrate ,by experimental and simulated results, that when the inlet is defined with multiple secondary branches using the algorithm proposed in our previous work, [13], the flow is closed to be homothopycal. All of this works, as well as the present paper, are partial results of the [17].

ACKNOWLEDGEMENTS

This research work is financially supported by Project DPI2007-66723-C02-02 from the Spanish Government and project PRCEU-UCH13/08 of the University CEU Cardenal Herrera.

References:

1. J.F.A.Kessels, A.S.Jonker, R.Akkerman, Optimising the flow pipe arrangement for resin infusion under flexible tooling, Comp.. Part A 38(2007), pp. 2076-85.
2. Hsiao K-T, Devillard M., Advani S.G. Simulation based flow distribution network optimization for vacuum assisted resin transfer moulding process. Model Simul. Mater. Sci. Eng. 2004;12:175-90.
3. Cai Zhong. Analysis of mold filling in RTM process. J Compos Mater 1992;26(9):1310-38.
4. Young WB. Gate location optimization in liquid composite molding using genetic algorithms. J. Compos Mater 1994;28 (12):1098-113.
5. Boccard A, Lee Wi, Springer GS. Model for determining the vent locations and the fill time of resin transfer molds. J Compos Mater 1995;29(3):306-23.
6. Mathur R, Fink BK, Advani SG. Use of genetic algorithms to optimize gate and vent locations for the resin transfer molding process. Polym. Compos 1999;20(2):67-78.
7. Luo J, Liang Z, Zhang C, Wang B. Optimum tooling design for resin transfer molding with virtual manufacturing and artificial intelligence. Compos Part A 2001;32:877-88.
8. Jiang S. Zhang C. Wang B. Optimum arrangement of gate and vent locations for RTM process design using a mesh distance-based approach. Compos Part A 2002;33:471-81.
9. Gokce A, Hsiao K, Advani SG. Branch and bound search to optimize injection gate locations in liquid composite molding process. Compos Part A 2002;33:1263-72.
10. Jiang S. Zhang C., Wang B. A process performance index and its application to optimization of the RTM process. Polym. Compos 2001;22(5):690-701.
11. F. Sánchez, J.A. García, F. Chinesta, Ll. Gascón, C. Zhang, Z. Liang, B. Wang, A process performance index based on gate-distance and incubation time for the optimization of gate locations in liquid composite molding processes, Compos Part A, 903-912, Vol.37/6, 2005.
12. N.Montés, F.Sánchez. A New computational tool for liquid Composite Moulding Process design based on configuration spaces. Compos. Part A. Vol 41,1, pp 58-77. January 2010.
13. N.Montés, F.Sánchez. A simplified approach of the channel distribution design in resin infusion process based on configuration spaces. Journal of Polymer composites, under review.
14. T.Ju, R.Goldman. Morphing Rational B-Spline curves and surfaces using mass distributions. Eurographics 2003.
15. A.W.F.Lee, D.Dobkin, W.Sweldens, P.Schorödes. Multiresolution mesh morphing. Proceedings of SIGGRAPH 99. pp. 343-350, August 1999
16. N.Montes, L.Domenech, U.Pineda, F.Sanchez. Inverse engineering application for the resin infusion process design. Int. J. of Mat. Forming. 2009. Under review.
17. PhD N.Montes. Marco Computacional para el diseño, optimización y control de procesos de moldeo con resinas liquidas(LCM). Summer 2009.