Fast and reliable gate arrangement pre-design of resin infusion processes

F.Sanchez[1*], L.Domenech[1], V.Garcia[1], N.Montes[1], A.Falco[1], E.Cueto[2], F.Chinesta[3], P.Fideu[4]

[1] *Universidad CEU Cardenal Herrera, C/San Bartolomé 55 (Moncada), Valencia, Spain*

[2]*Aragon Institute of Engineering Research. Universidad de Zaragoza, Spain*

[3]*Institut de Recherche en Génie Civil et Mécanique, Ecole Central de Nantes, Nantes, France*

[4]*Airbus Deutchland GmbH, Kreetslag 10, 21129 Hamburg Germany*

**Corresponding author's e-mail: fernando.sanchez@uch.ceu.es*

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Abstract

In Resin Infusion (RI) processes, the flow front shape progression is mainly conditioned by the initial arrangement of the injection and vent gate line locations and the permeability of the preform. The main goal of this research is to develop fast (not necessarily physically-based) tools at the pre-design stage that could help designers with a suitable arrangement of injection nozzles and vents. This pre-design should then be validated by full-physics simulation or lab test, but could be considered as a suitable starting point in the designing process. RI simulators could eventually be equipped with this kind of pre-design tools as a means to provide very fast (at the cost of a somewhat reduced accuracy) designs. In the approach here presented the pre-design tools are based entirely on geometrical assumptions. Under these hypotheses, and assuming that the vents will be placed on the boundary of the piece, the distance field from this boundary will provide useful information on the optimal

position of injection nozzles. In this work, inspired by the concept of medial axis, we propose a numerical technique that computes numerically approximate distance fields by invoking computational geometry concepts that can be used for the estimation of the gate arrangement in infusion processes. Detailed descriptions of the developed algorithm, together with first proofs of its performance are given.

1. Introduction

Resin Infusion (RI) processes are one of the common techniques used in the industry for large composite parts production. This technique uses negative pressure to drive the resin into a laminate. Preform is laid dry into the mold and the vacuum is applied before the resin is introduced. Once the difference between fluid pressure levels at the inlet and the outlet is achieved, resin is sucked into the laminate via placed tubing. Fig. 1 (left) shows a diagram of this process. Process designers introduce a resin inlet channel network in the areas where the cosmetic quality of the piece is not relevant; see Fig. 1 (left). Resin infusion processes are usually slow due to the low-pressure gradient and the size of the geometries to infuse. For this reason, the channels are necessary to reduce cycle times. Using it as in Fig. 1 (left) the filling of a boat hull with 11.8 m length can be completed in 195 min. Spiral blind (pipes), has been commonly used to build these channels, Fig. 1. These components are hollow tubes made with a plastic strip rolled in a spiral shape. The resin flows much faster inside the pipe than inside the preform. When the resin fills the channel, it begins to permeate the preform through the holes left by the spirals.

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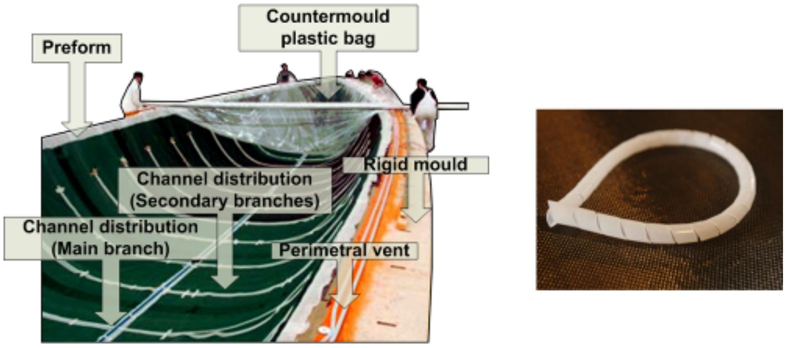

Fig. 1. *Resin Infusion Process (left). Spiral blind, pipe, (right).*

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Nowadays, the problem comes to optimize the shape and allocation of these channels. In general, optimization algorithms proposed in the literature have been based on Finite Element (FEM) simulation coupled with genetic algorithms, mainly focused in RTM problems. These algorithms have a high computational cost (hours) to find an acceptable solution. Researchers have been working intensively to propose alternatives to the standard FEM simulation based genetic algorithms. In [3] the use of neural networks was proposed to replace the simulation, meanwhile in [4] [11] the distance between the nodes of the mesh was used as a filling-time approximation. In [2] [6] gradient-based methods were introduced to improve genetic algorithms. In [5] a proposal was made to replace the genetic algorithm for the "*branch and bound*" technique. Another possibility that was analyzed in the literature was based on a map-based exhaustive search, [9], where the probabilities of all the possible node vents were computed. This algorithm was combined in [8] to the "*branch and bound*" technique. The objective function was based on the reduction of the filling times, prevention of dry areas, homogeneous curing, etc. These indexes are known as "Process Performance Index (PPI)". In the optimization algorithms proposed in [1][4][5][6][8][9], the parameters used on them were the filling time and the prevention of dry areas. In [12] an index with the same objectives than the ones proposed [1][4] was introduced. However, dry areas were prevented by the correct orientation of the flow front with respect to the vent. This index was improved in [13] with the inclusion of the incubation time parameter.

Most of the optimization algorithms proposed in the literature focused in solving the inlet/outlet location in RTM [1]-[11]. A few exceptions [10] [11] addressed the optimization of flexible countermould processes that involve complex shapes as shown in Fig. 1.

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The aim of the optimization algorithms in LRI processes is the same than in RTM: the flow front must reach the vent (in LRI, the mould contour) at the same time and the filling time must be reduced as much as possible. To the author's knowledge, the literature does not offer tools to compute efficiently such a problem. The main reason is that in LRI processes, the inlet adopts complex configurations and accurate optimizations require too many direct solution of the filling process for each tentative inlet arrangement. However, the industry and, in particular, expert teams have the ability to design the resin channel distribution and getting amazing results. These expert teams use trial and error and their large experience, to obtain the optimal resin channel distribution, like the one depicted in Fig. 1.

The aim of our previous works was to obtain a tool to compute the resin channel distribution using the expert team criterion, [14] [15], in an automated way and with acceptable computational costs. In these works, the optimal channel distribution was divided in two parts: the "*main branch*" and "*secondary branches*", see Fig. 1. Main branch was obtained by applying the Delaunay triangulation to the vent (the mold contour). This algorithm provides the vertexes to be tangent with at least three contour points, see Fig. 2.

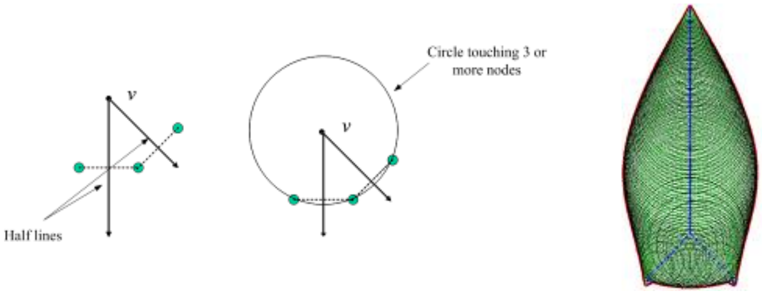

Fig. 2. *Main branch computation (Left). Example of a Boat (Right)*

This *Main branch* was improved in [14][15] by means of the same concept: the use of secondary branches. Therefore, each secondary branch is equidistant to at least two contour nodes. Then, the bisector between these two nodes, passing through the tangency circle center, intersects in a main branch point. The secondary branch was defined from the intersection point of main branch to the circle center that ensures the tangency, see Fig. 3.

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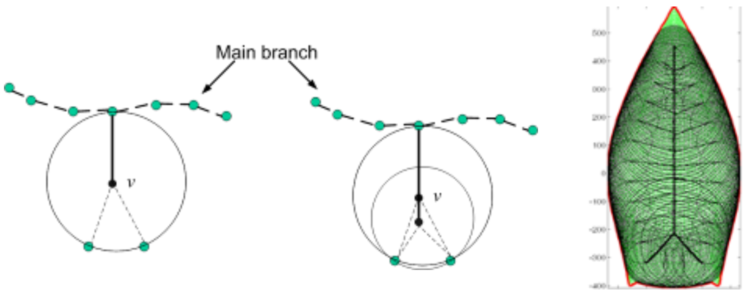

Fig. 3. *Secondary branch computation (Left). Example of a Boat (Right)*

The main objective of this work is to develop fast numerical tools based on computational geometry concepts and use them as processing indicators to be used in pre-design stages. These numerical indicators are computed based on the naïve idea that as soon as the flow front is equidistant to the mould vent, it will reach simultaneously the vent and consequently the filling process will be optimal. Obviously, in general, such a solution does not exist if we proceed in one-shot with all the channels connected and simultaneously triggered. However, the optimal inlet gate arrangement can be searched for maximizing such criterion.

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2. Objective and problem outline

LCM simulation is computationally expensive because it needs an accurate solution of flow equations during the mold filling process. Nowadays large computing times are not compatible with standard design and optimization techniques (many-query approaches) to determine in a nearly-optimal way the injection and vent gates. Nor with simulation-based process control that in general requires fast decision making. The main objective of this research (see also previous works [13], [14] and [15]) is to develop fast computational tools that should provide the designer with a valid pre-design strategy, possibly at the price of some loss of accuracy, but orders of magnitude faster that standard physics-based simulation. Our objective is not to substitute standard simulation techniques, but to provide the designer with a real-time tool able to suggest a near-optimal design of injection nozzles and vents. This design should then be validated by standard, physics-based simulation, but without the need for many trial-and-error loops in the design pipeline.

This pre-design tool will be based on the next main assumptions:

1. Uniform, homogeneous and isotropic permeability of the fiber preform states a correspondence between distance and filling time.
2. Injection from the vents would determine the location of the injection nozzles as the set of farthest points from the boundary, which closely resembles the concept of medial axis of the piece.

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These assumptions will be modified accordingly to take into account the existence of holes, obstacles or non-uniform permeability distribution.

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In this work, inspired by the concept of medial axis [16], we propose a numerical technique that computes numerically approximate distance fields from the boundary (or in general, from the position of vents) by invoking computational geometry concepts that can be used for the estimation of the gate arrangement in infusion processes. The fulfilled procedure should give the capabilities to define an initial inlet design. Accomplishing a full-physics simulation of the process must therefore validate this design.

It is important to note that the technique that follows avoids any physical simulation of the process and is based entirely on geometrical assumptions. This will certainly produce a loss of accuracy with respect to state-of-the-art numerical simulation techniques, but (i) is orders of magnitude faster and (ii) avoids most of the trial-and-error calls to simulation codes. It is expected that one single final simulation will provide the validation of the pre-design provided by this technique, therefore saving most of the computational cost needed for today's design process.

We first introduce an algorithm based on the use of level sets in RI modeling to compute geometrical indicators of the positioning of injection nozzles. These are discussed later in next section as numerical tools in application of a particular case for the Resin Infusion process gate arrangement pre-design. A completed algorithm showing the capabilities of the procedure is also outlined.

3. A Fast Marching-Level Sets approach for the distance field computation

Based upon assumptions 1 and 2, a fast marching-level set approach is employed to compute the vent distance field of a given part. An easy and fast way to compute a distance field, expressed as an implicit function $\phi(x,t)$, is to employ a level set approach, in particular the Fast Marching method provides very fast results at a minimum computational cost [17].

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The evolution of an implicit function under an external velocity field can be written as

$$\phi_t + v \cdot |\nabla\phi| = 0, \qquad (1)$$

where sub-index indicates a partial derivative with respect to that variable. We assume that the velocity field at the flow front is normal to the implicit function ϕ itself, $v = V_n n$ with V_n constant and n outwards unit vector. Note that the evolution of ϕ under $|\nabla\phi| = 1$ and a unit normal velocity produces a distance field and therefore the equation to integrate in time has a simpler form:

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$$\phi_t = -1, \qquad (2)$$

see [17] for details on the discretization, initialization and integration of these equations by the fast marching method.

Once the distance function $\phi(x,y)$ has been computed in the whole domain, we can define some geometric concepts that will be used in the numerical proposal of the RI modeling.

Fig. 4 depicts an example of the distance function computed over a squared domain. In this case, the zero-level set of the function is assumed to be located at the vents position, i.e., the boundary of the square. It can be readily noticed that the just computed level set function possesses a maximum value at the center of gravity of the square, with a value of 50 units.

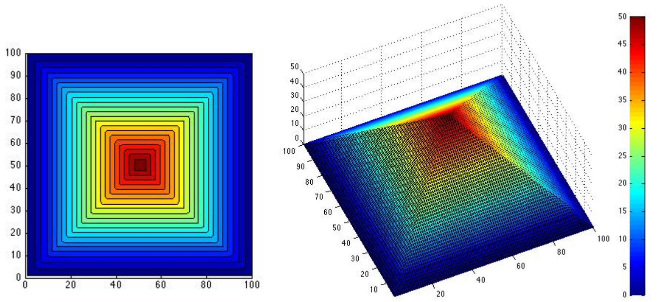

Fig. 4. Distance function $\phi(x,y)$ computed inwards from the vent contour.

However, this approach does not provide any useful result by itself, since an injection from the square center will produce, in homogeneous and isotropic conditions, a circular flow front that is distant from being an optimal solution for this problem.

On the contrary, the *medial axis* of the boundary of the square (assumed to represent the position of the vents, as stated repeatedly before), defined as the locus of the points having more than one closest point on the object's boundary, provides a more convenient means to define a set of injection nozzles. An easy and fast way to compute the medial axis on the basis of the just computed distance field is introduced below.

3.1. *Edge Pattern function Λ*

A very convenient means to determine the medial axis of the boundary of the part consist in computing numerically the Laplacian of the distance field $\Lambda=\phi_{xx}+\phi_{yy}$, because second derivatives identify large curvatures as illustrated in Fig. 5. This function $\Lambda(x,y)$ corresponds to the medial axis in the case of having an homogeneous permeability domain and states the set of points that are equidistant to at least two points of the boundary of the part.

Since permeability variations in the reinforcements would alter the velocity field during the process, and it is not clear how this would affect the position of the medial axis, we propose here an alternative algorithm to compute the equivalent medial axis that is amenable to changes in the permeability values of isotropic reinforcements throughout the piece.

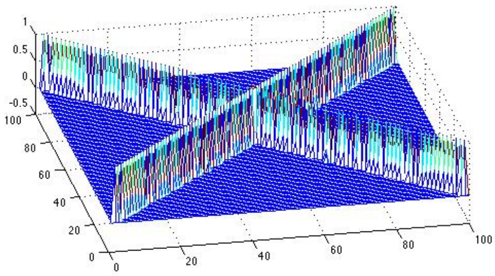

Fig. 5. Edge Pattern function $\Lambda(x,y)$ computed from the distance function depicted in Fig. 4

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4. Application in the Resin Infusion gate arrangement pre-design based on Level Set

In order to show the capabilities of the proposed technique, we present in this section an algorithm that computes a particular strategy in the pre-design of RI gate arrangement. We will show the use of the distance function based fast marching computations and the potentials of the geometric indicators defined in the previous section in a comprehensive 2D part. Since the fast marching method is not limited to 2D geometries, it can be straightforwardly extended to a more complex part.

One can define a RI mold filling strategy conditioned by many considerations like geometrical features, material properties characterization, production technological devices disposability, or production optimization objectives (mainly economical or for quality part assurance). In this work, a 'one shot' filling strategy with a continuous connected injection gate arrangement is considered as a particular case. Other possibilities such as sequential fillings or disconnected gate lines are not considered so far so as to focus on the potential of the method to solve a particular problem, although they will be analyzed in a near future. Nevertheless, many other strategies not fully covered in this example can be developed with different restrictions using the same criteria that distance fields and Edge Pattern functions offer as geometric indicators.

The application example described below show in five steps the capability of the procedure with the definition of the main branch and secondary branches of a channel network layout by means of the Distance field computation and the Edge Pattern function.

4.1. Application example: One shot filling strategy with an all-connected distribution channel and secondary branches.

Preserving the RI assumptions stated in section 2, we work out an example, see Fig. 6, where we assume the vent vacuum line is located on the boundary contour of a 2D-rectangular part. An interior obstacle (upper right) defines a hole and, in this particular case, it is treated also as a vent line (otherwise it could be filled with resin without defining a hole). Moreover, the part has two discontinuous regions of different permeability (middle left band permeability is doubled, k2>k1) that yields complex flow progression and velocity field variations in these areas.

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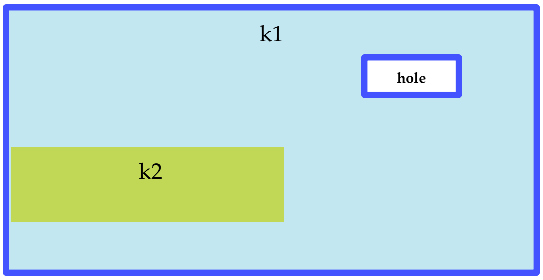

Fig. 6. Part Geometry and textile regions. Different permeabilities are considered in green and blue regions, whereas dark blue lines indicate vent lines

Step 1. Compute the distance field $\phi(x,y)$ function inwards from the boundary vent contour. The distance field is obtained for the whole domain of a given piece.

In Fig. 7 and Fig. 8, the distance of each location to the vent line is shown, defined on the boundary of the part. It is important to note the assumption of the correspondence between distance and time from the boundary vent contour to an isoline. It is computed with the fast marching algorithm introduced in previous sections. Each isoline has the same distance value from the closest (in blue) to the farthest location (in red).

There are two interesting geometric features that worth a comment. The first one is that the hole located in the upper right side of the part is defined as vent line. Hence, the distances are also computed from the hole. This method of calculating distances allows one to treat easily with not-simply-connected spaces. Since the holes/obstacles can produce flow front encounters with air entrapments, the technological solutions can be achieved in terms of considering the holes/obstacles as part of the inlet/outlet or even ignoring them for post-processing cutting. In our case, it can be solved assuming that the holes/obstacles have to be connected to the vacuum contour line of the mold.

The second important feature is to observe how the method handles the textile (permeability) variation regions. In the middle left band defined with an isotropic textile with a permeability double than in the whole domain, the level set evolution is computed with a double value of the velocity field in that region, i.e., $|\nabla\phi| = 2$ in Eq.(2). Subsequently, the distance field is solved assuming this flow behavior affecting also the distance computation of its neighborhood, and hence the separation between isolines in Fig. 7 appears doubled.

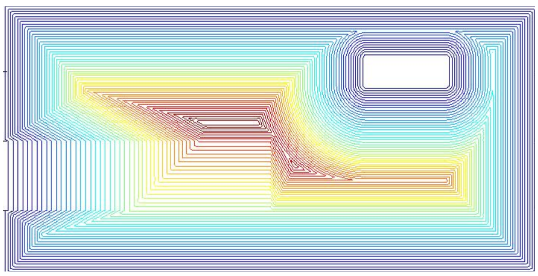

Fig. 7. *Distance function ϕ(x,y) computed inwards from the vent line located on the boundary of the part and the hole (obstacle)*

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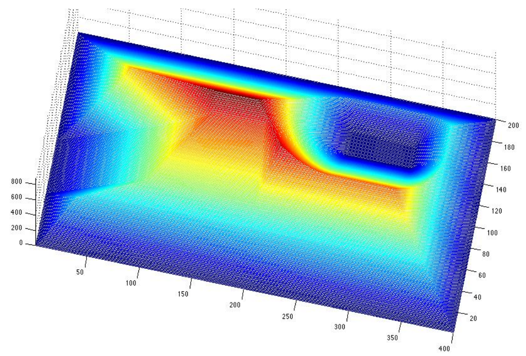

Fig. 8. *3D representation of the distance function ϕ(x,y) where the edges are observed*

Step 2. The Edge Pattern Λ(x,y) is computed from ϕ(x,y) of step1. An arrangement of the mold distribution channel, Main Branch, is defined.

Under the previous assumptions, the problem of obtaining the best resin channel distribution becomes a geometric problem that can be solved with the *Edge Pattern Λ(x,y)* that defines for the whole domain, the set of points that are equidistant to at least two points of the vent line.

In Fig. 9 the resulting *Edge Pattern function* $\Lambda(x,y)$ is shown. It is important to note, however, that since the straightforward computation of the medial axis (or, equivalently, the Laplacian $\Lambda(x,y)$) touches the vent line, a production criteria has to be established so as to define the total filling time of the part. The more length of the channel runner, the better for decreasing the total filling time, but also need more materials and more operations for placing tubes. In our approach, based on distance field computation, it can be accounted for by defining a parameter τ that imposes the minimum distance of the distribution channel to any location of the mold boundary, see Fig. 10. In our methodology, this minimum distance is set in the whole domain by an isoline value of the distance function $\phi(x,y)$. This parameter τ can be well adjusted and obviously defines the optimal solution as the one where the resin losses are minimum (the fast optimization constitutes a work in progress and consequently it is not addressed in the present work). For the purposes of this application example it has not been fully optimized, but anyway, its definition as a main branch, see Fig. 11, is coupled with the channel secondary branches definition that are outlined in what follows.

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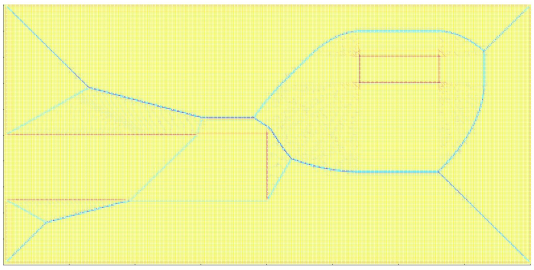

Fig. 9. Edge Pattern function $\Lambda(x,y)$ computed with the laplacian of $\phi(x,y)$

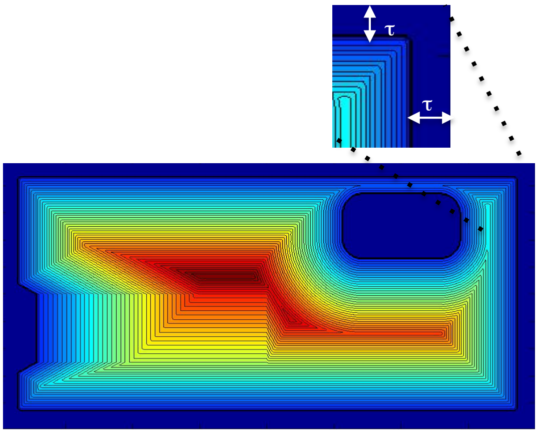

Fig. 10. Distance function $\phi(x,y)$ and $\boldsymbol{\tau}$ parameter correlated with the total filling time.

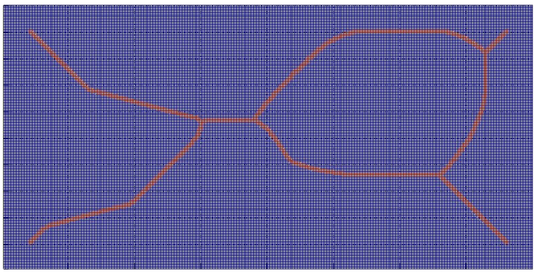

Fig. 11. Distribution channel arrangement defining the ***Main Branch***

Step 3. Preliminary Secondary Branches Definition avoiding dry spots and imposing uniform vent arriving.

In order to obtain an appropriate filling strategy, we assume that the injection line design has to guarantee that the resin reaches the vent line as uniformly as possible, and avoiding dry spots and flow encounters. Noteworthy, since the location of the points of the medial axis defined in step 2 are not all equidistant to the vent, it is necessary to overcome possible losses of resin with the generation of Secondary Branches. They are also needed to avoid dry spots.

The algorithm here presented defines independent regions based on the Main Branch computation of the previous step and on the value of the parameter τ, see Fig. 12. To generate secondary injection branches, a second distance field $\phi_A(x,y)$ is computed outwards (i.e., from the inlet obtained previously as a main branch, see Fig. 13.)

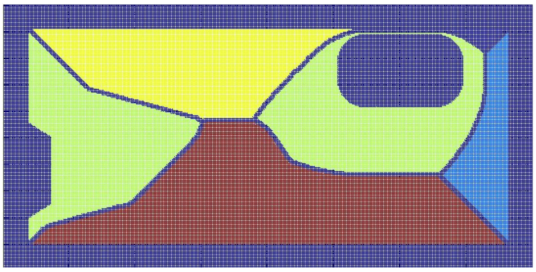

Fig. 12. Independent regions defined from the Main Branch and total filling time parameter τ

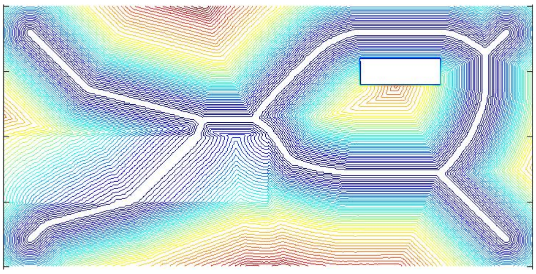

Fig. 13. Distance field $\phi_2(x,y)$ computed outwards from the main branch

This second distance field $\phi_2(x,y)$ provides an intuitive idea of regions of the piece being filled at longer times (ideally all the points belonging to the boundary, i.e., to the vent, should have roughly the same distance to the injection nozzles). In order to have a resin flow arriving uniformly to the vent, a set of Secondary Branches is included for each of the regions defined previously, see Fig. 14.

The branches are generated computing the streamlines of the distance function $\phi_2(x,y)$ from the vent line. We consider that the branches are defined from the isoline defined with τ to the intersection with the Main Branch. Moreover, we impose that two consecutive branches of the same region have to be regularly separated a maximum distance defined of the double of τ along its path, see Fig. 14 and Fig. 15 for a particular solution.

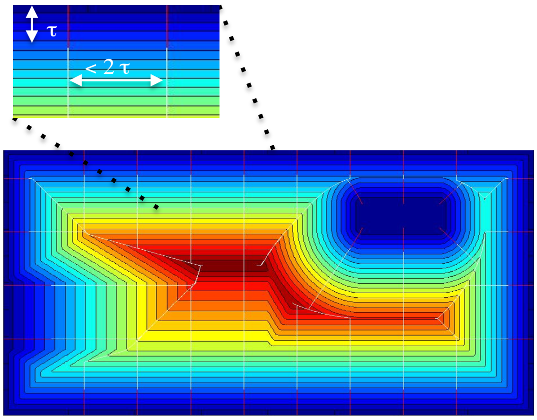

Fig. 14. *Streamlines of the distance field $\phi_2(x,y)$ for secondary branch generation.*

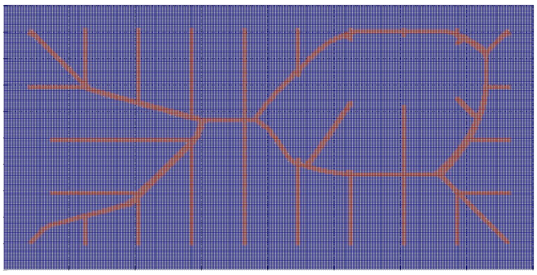

Fig. 15. *Preliminary inlet gate arrangement with main and secondary branches*

Step 4. Additional Secondary Branches Definition avoiding dry spots for a vent oriented flow.

The algorithm defines again independent regions based on the previous arrangement obtained in the step 3, Fig. 16. Again, a third distance field $\phi(x,y)$ is computed outwards from the inlet obtained, see Fig. 17, and hence possible dry spot are outlined. Additional secondary branches are added to the previous arrangement only in those areas, see Fig. 18. Step 4 is computed iteratively until no additional branches are required. See Fig. 19 and Fig. 20. In our example, just one additional iteration is required.

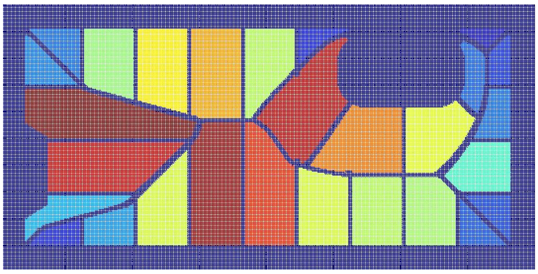

Fig. 16. Independent regions defined from the preliminary gate arrangement and parameter τ

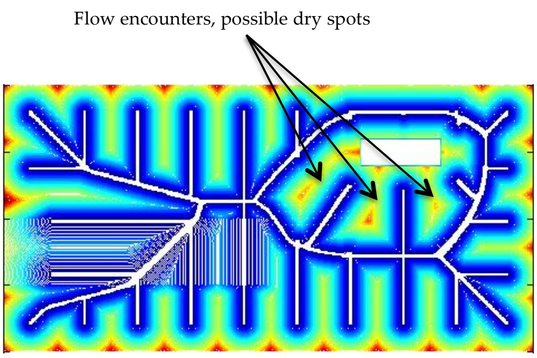

Fig. 17. Distance function $\phi(x,y)$ computed outwards from the previous arrangement

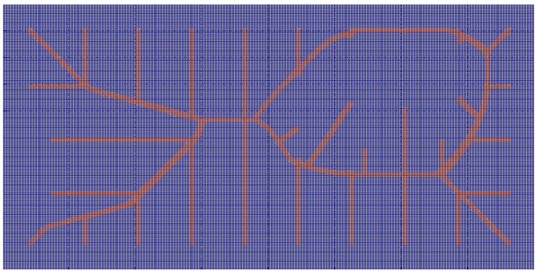

Fig. 18. Inlet gate arrangement with additional Secondary Branches avoiding dry spots

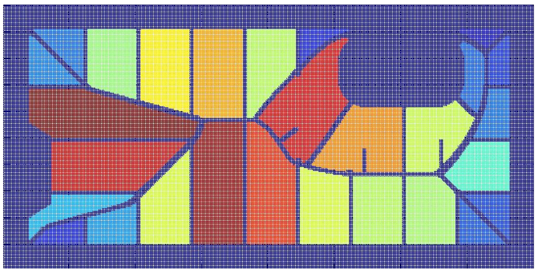

Fig. 19. Independent regions defined from the previous arrangement

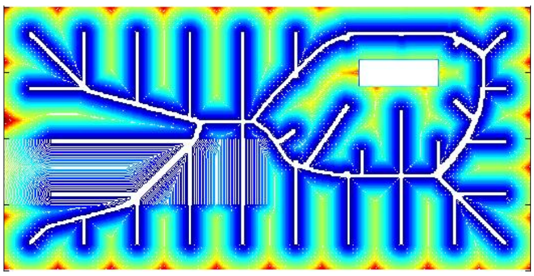

Fig. 20. Distance field $\phi_i(x,y)$ computed outwards from the previous arrangement guaranteeing no dry spots and almost uniform filling

Step 5. Physical simulation-based validation

The numerical procedure described in previous steps can iterate different options searching a continuous connected injection gate arrangement preserving the RI assumptions. In the case exposed in this work, the pre-design gate arrangement has been computed in just a few seconds. This gate layout has been used afterwards as a starting point in a complementary complete physical simulation that can be carried out with a FEM-CV approach (see for instance [18] for an appropriate validation of the resin flow pattern). There are different developments [19][20][21], or commercial codes to carry out appropriate numerical simulations. Obviously, appropriate material and geometry models are necessary for evaluating quantitatively the manufacturability of the channel layout scheme based on the physical simulation iterated results. Nevertheless, it does not fall within the scope of this work.

Fig. 21 shows Darcy's flow simulated in order to validate the pre-design approach. It is noticed how the flow achieves almost uniformly the vent without dry spots.

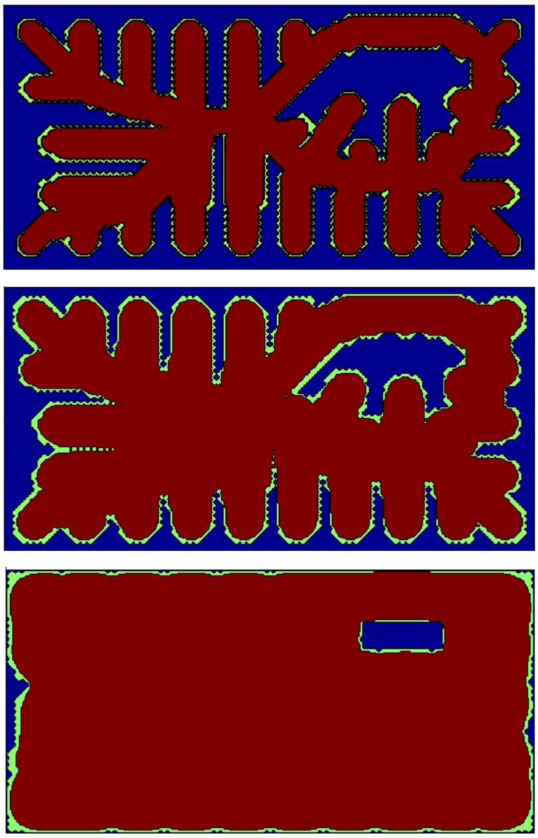

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Fig. 21. Flow front evolution in three different time steps for the inlet arrangement defined in step 4, see Fig. 18

5. Conclusions and Future Work

In RI, the flow front progression is mainly conditioned by the initial arrangement of the injection and vent gate line location and the permeability of the preform that evolves throughout the mold.

In this work a RI modeling approach is proposed, based on considering a distance field computation in order to have a pre-design numerical tool for fast and reliable process strategy estimation. This technique treats the resin flow front in a simplified manner that allows one to use it as a very fast pre-design tool to predict the flow behaviour in different prescribed process and material conditions. This pre-design should then be computed by full-physics simulation or lab test for a better accuracy and manufacturability validation, but could be used as an acceptable starting point in the designing process.

A fast marching - level set approach is used to model non-physically the different alternatives for the estimation of the front shape evolution during filling. In order to show the capabilities of the proposal, it has been presented an algorithm that computes a particular strategy in the RI gate arrangement pre-design. In this work, a 'one shot' filling strategy with a continuous connected injection gate arrangement has been stated as a RI particular strategy case. The main limitation of this procedure is to omit the through-thickness flow in the reinforcement for a 3D part and the anisotropic permeability. These topics are right now under further research. A first approach to scope non-isotropic textiles is to include the effect of the permeability tensor in the velocity field when computing the distance function. These and other possibilities, such as sequential fillings or disconnected gate lines are not yet considered, although constitute our main effort of research at this moment.

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