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CONSTRUCTAL DESIGN APPLIED TO THE LIGHT RESIN TRANSFER MOLDING (LRTM) MANUFACTURING PROCESS

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Abstract. *The Light Resin Transfer Molding (LRTM) is a manufacturing process where a closed mold pre-loaded with a porous fibrous preform is filled by a liquid resin injected through an empty channel (without porous medium) which runs all around the perimeter of the mold, producing polymeric composite parts. Using the capability of FLUENT® package to simulate a multiphase flow (resin and air) in a geometry composed by porous media regions and empty regions, a computational model based on the Finite Volume Method (FVM) was applied to reproduce the resin flow behavior during the LRTM process. The aim of this work was to define the optimal geometry for the empty channel (border) by means the Constructal Design method. To do so, considering a border with a rectangular cross sectional area, the degree of freedom* w_b/t_b *(ratio between the width and thickness of the border) can vary while the border volume is kept constant. The results showed that employing the Constructal Design it is possible to decrease the filling time of the LRTM process in almost 20 %, being this an unpublished use for the Constructal Theory.*

Keywords: *Light Resin Transfer Molding (LRTM), Constructal Design, Geometric Optimization, Numerical Simulation, Computational Modeling.*

1. INTRODUCTION

Nowadays the use of composite materials to replace the traditional materials in different areas of engineering is a fact. Their attractive properties when compared with isotropic materials, such as higher stiffness/weight, higher strength, higher damping and good properties related to thermal or acoustic isolation, explain the employment increases of the composites in aeronautical, aerospace, automotive, naval and other industries.

There are several industrial techniques for the manufacturing of composite materials. Among them, the Liquid Composite Molding techniques, such as the Resin Transfer Molding (RTM) and its variations, are considered attractive processes to obtain polymeric composite parts with complex shapes and features, as well as, with good quality. In the RTM process, in general, a fibrous preform is placed in a female mold while the male mold closes leaving a nozzle by which the polymeric resin is injected to impregnate the preform. A technology derived from the conventional RTM process is the Light Resin Transfer Molding (LRTM) process, where the resin injection into the mold is performed by an injection channel, without fibrous reinforcement, existing on the perimeter of the mold. As well as in the RTM process the mold cavity is previously filled with the fibrous reinforcement, however in the LRTM vacuum is used to drive the resin through this preform until its complete impregnation. One can find several publications about the RTM process, where experimental, analytic and numerical approaches are broadly discussed (Schmidt et al., 2009; Hattabi et al., 2008; Rudd, 2005; Shojaei et al., 2004; Yang et al., 2008), but the LRTM manufacturing process has not been sufficiently reported by the scientific community.

So, taking into account the above exposed, this work presents a computational model for the LRTM process that was used coupled with the Constructal Design method to determine the optimal dimensions for its empty injection channel (called border) to manufacture a rectangular box.

The Constructal Design method is based on the Constructal theory, which has been used to deterministically explain the generation of shape in flow structures of nature (river basins, lungs, atmospheric circulation, animal shapes, vascularized tissues, etc) based on an evolutionary principle of flow access in time. That principle is the Constructal law: for a flow system to persist in time (to survive), it must evolve in such way that it provides easier and easier access to the currents that flow through it (Bejan and Lorente, 2008). This same principle is used to yields new designs for electronics, fuel cells, and tree networks for transport of people, goods and information (Bejan and Lorente, 2006a). The applicability of this method/law to the physics of engineered flow systems has been widely discussed in recent literature (Beyene and Peffley, 2009; Kim et al., 2010; Kim et al., 2011; Azad and Amidpour, 2011).

2. LIGHT RESIN TRANSFER MOLDING (LRTM) PROCESS

As already mentioned, the LRTM process is a variation of the conventional RTM manufacture and can be defined as a vacuum-assisted RTM with low-pressure resin injection system. A peripheral vacuum is used for clamping, whereas positive pumping pressure, combined with a controlled cavity vacuum, produces consistent composite parts. In the LRTM, at least one side of the mold is made of a fairly flexible material than the near-rigid mold of conventional RTM. The mold is normally translucent, enabling monitoring the progress of the resin flow within the mold. Besides, as the resin is injected peripherally in the LRTM mold, its flow converges to a central outlet nozzle.

One of the main advantages of the LRTM is that the mold can be closed and the fibrous preform can be compacted under a compaction-force which is less than that required in the RTM process, leading to cost and time savings.

Although the LRTM process has a great applicability to produce composite parts used in engineering applications, the technical literature about this manufacturing process is recent and scarce. Some examples of these publications are: Garay et al. (2011), Isoldi et al. (2012), Porto et al. (2012).

3. CONSTRUCTAL DESIGN

It is possible to state that improving systems configuration for achieving better performance is the major goal in engineering. In the past, the scientific and technical knowledge combined with practice and intuition has guided engineers in the design of man-made systems for specific purposes. Soon after, the advent of the computational tools has permitted to simulate and evaluate flow architectures with many degrees of freedom. However, while system performance was analyzed and evaluated on a scientific basis, system design was kept at the level of art (Bejan and Lorente, 2006a).

The Constructal Theory was created by Adrian Bejan, in 1997, when a new geometric solution philosophy was applied to the conductive cooling of electronics (Bejan, 1997; Bejan, 2000). These studies have a significant importance because they played a basic and starting point role for the extension and application of Constructal Theory to problems in engineering and other branches of science, such as social dynamics, urban design, traffic, transportation, economy and evolution of technology (Bejan and Lorente, 2008; Ghodoossi, 2004). Moreover, Constructal Theory has been employed to explain deterministically the generation of shapes in nature (Bejan, 2000).

The Constructal Theory states that: “for a flow system to persist in time (to survive) it must evolve in such a way that it provides easier and easier access to the currents that flow through it”. It is not only a principle from which geometric shape and structure are deduced, but also an engineering method for optimizing the paths for flows through finite-size open systems (Bejan and Lorente, 2006b).

This is a major step toward making system design a science. This theory indicates that if a system is free to morph under global constraints, the better flow architecture is the one that minimizes the global flow resistances, or maximizes the global flow access. A basic outcome of the Constructal Theory is that system shape and internal flow architecture do not develop by chance, but they result from the permanent struggle for better performance and therefore must evolve in time. As in engineered systems, in nature the competition is permanent (e.g., river basins, global circulations, trees and animals morph and improve in time under changing constraints) (Bejan and Lorente, 2006a).

Concerning the engineering problems, the applicability of Constructal Design (Constructal Theory for optimization of several systems, e.g., engineering) has been dominantly applied for the study of fluid mechanics and heat transfer. In the fluid mechanics realm, Bejan (2000) and Bejan and Lorente (2008) showed that the pressure drop for flows in ducts with round cross-section are minimal in comparison with the pressure drops reached for other several regular polygonal cross sections. Examples of vascular tree-shaped flow architectures employed to guide river basin design are also presented in Bejan (2006) and Reis (2006). Cetkin et al. (2010) studied the configuration of vascular channels when the flow is turbulent. Moreover, Constructal Design has also been employed for the optimization of internal and external flows submitted to convection heat transfer, e.g., in Bello-Ochende et al. (2011), Kim et al. (2010) and Rocha et al. (2009).

Therefore, in this work the Constructal Design method was adopted to determine the optimal geometry for the empty channel (border) by which the polymeric resin is injected in the LRTM manufacturing process, having as objective function the minimization of the final filling time. To do so, a border with a rectangular cross sectional area was considered where the degree of freedom (DOF) defined by the ratio between its width (w_b) and thickness (t_b), i.e., w/t. While the border volume fraction $\phi = V_b/V_p$ (ratio between the border volume and the part volume) was kept fixed, characterizing a constraint of the geometric optimization procedure, the DOF w/t is varied. To compare the several possible geometries a numerical approach was used. More details about the numerical model as well as the geometry dimensions for the LRTM problem analyzed is presented in the next section.

4. COMPUTATIONAL MODELING

In the LRTM process, the resin is injected into the empty border by an inlet nozzle. There is a tendency that the resin fill the border firstly. After that the resin flows through the fibrous reinforcement, which can be considered as a porous medium. As the resin progresses the air is expelled out of the mold cavity through the outlet nozzle. Thus, there is a multi-phase flow during all manufacturing process. However, in the second stage the flow can be assumed to follow the Darcy's Law, which states that the flow rate of resin per unit area is proportional to the pressure gradient and inversely proportional to the resin viscosity (Bejan, 2004; Morren et al., 2009).

In the context of fluid mechanics, multi-phase flows can be taken as simply any fluid flow system consisting of two or more distinct phases flowing simultaneously in mixture, having some level of phase separation at a scale well above the molecular level. Multi-phase flows can, in general, exist in many different forms. Depending on combinations of phases, two-phase flows can be classified according to the state of the different phases: gas-solid flows or liquid-solid flows or gas-liquid flows (Yeoh and Tu, 2010). Hence in the LRTM process there is a gas-liquid multi-phase flow, composed by the air and the polymeric resin. To tackle the interaction between the air and the resin during the LRTM process the Volume of Fluid (VOF) method was employed. The VOF method relies on a scalar indicator function between zero and unity to distinguish between these fluids, the so-called volume fraction (α). A value of zero for α indicates the presence of one fluid (air) and a value of unity indicates the presence of second fluid (resin). On a computational mesh, volume fraction values between these two limits indicate the presence of the interface and the value provides an indication of the relative proportions occupying the cell volume (Yeoh and Tu, 2010).

In the VOF method the momentum, continuity and volume fraction transport equations must be solved simultaneously. In this work the VOF solution is obtained by FLUENT® software – a general CFD (Computational Fluid Dynamic) package, based on the Finite Volume Method (FVM) – which includes a VOF module for the solution of problems with two or more immiscible fluids where the position of the interface between the fluids is of interest (FLUENT, 2008). A single set of momentum equations is applied to both fluids, and the volume fraction of each fluid in every computational cell is tracked throughout the domain (FLUENT, 2008; Isoldi et al., 2012).

Thus, the model is composed by the continuity equation, given by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho V_i \right) = 0 \; ; \tag{1}$$

the equation for the resin volume fraction α, defined by:

$$\frac{\partial \left(\rho \alpha \right)}{\partial t} + \nabla \cdot \left(\rho \alpha V_i \right) = 0 \; ; \tag{2}$$

and the momentum equation given by:

$$\frac{\partial \left(\rho V_i \right)}{\partial t} + \nabla \cdot \left(\rho V_i V_i \right) = -\nabla P + \nabla \cdot \left[\mu \tau_{ij} \right] + \rho g_i + F_i \; ; \tag{3}$$

being ρ the density (kg/m^3), t the time (s), ∇ is the gradient operator, V_i the velocity vector (m/s), P the pressure (Pa), μ the absolute viscosity (Pa·s), τ_{ij} the stress tensor (Pa), g_i the gravitational acceleration vector (m/s^2), F_i an external force vector (N) and indexes $i, j = 1, 2, 3$ representing the x, y and z directions, respectively. As only a single set of momentum and continuity equations is used for both phases, average properties for ρ and μ need to be defined. These properties can be approximated as (Srinivasan et al., 2011)

$$\rho = \alpha\rho_r + \left(1-\alpha\right)\rho_a \tag{4}$$

$$\mu = \alpha\mu_r + \left(1-\alpha\right)\mu_a \tag{5}$$

where the subscripts *r* and *a* indicating resin and air, respectively.

Moreover, as already mentioned, the reinforcement inside the mold cavity may be considered as a porous medium and formulated by the Darcy's Law. The mathematical formulation for this phenomenon is given by (Bejan, 2004; Morren et al., 2009):

$$V_i = -\frac{K_{ij}}{\mu}\nabla P \tag{6}$$

where V_i is the velocity vector of the resin flow (m/s), μ is the viscosity of the resin (Pa·s), K_{ij} is the permeability tensor of the fiber reinforcement (m^2), ∇ is the gradient operator, *P* is the injection pressure (Pa) and the indexes $i, j = 1, 2, 3$ representing the x, y and z directions, respectively. Considering both the resin and air with constant physical properties and an incompressible flow, the mass conservation equation can be stated as:

$$\nabla \cdot V_i = 0 \tag{7}$$

In FLUENT, porous media are modeled by the addition of a source term to the standard momentum equations such as (FLUENT, 2008):

$$F_i = -\frac{\mu}{K_{ij}}V_i \tag{8}$$

Combining Eq. (3) and Eq. (8) and considering that F_i is very large because K_{ij} is very small $\left(\sim 1\times10^{-10}\right)$ it is possible to simplify Eq. (3) as follows:

$$\nabla P = -\frac{\mu}{K_{ij}}V_i \tag{9}$$

One can note that Eq. (9) represents the Darcy's Law as well as Eq. (6).

The mathematical model presented was discretized by means the Finite Volume Method (FVM) in the FLUENT software. The solver is pressure-based and all simulations were performed employing the First Order Upwind and PRESTO! for spatial discretizations of momentum and pressure, respectively. The velocity-pressure coupling is performed by the Coupled method, while the GEO-RECONSTRUCTION method is employed to tackle with the volumetric fraction. Moreover, explicit relaxation factors of 0.75 are imposed for the conservation equations of continuity and momentum.

It is worth to highlight that this computational model has already been verified and validated in previous works of the research group, as in Isoldi et al. (2012), Oliveira et al. (2012) and Porto et al. (2012), and because of that these procedures will not be repeated here.

5. RESULTS AND DISCUSSION

The case studied in this work is a composite rectangular box manufactured by means the LRTM process, where the border dimensions can vary in accordance with the Constructal Design method aiming to minimize the total filling time. Figure 1 exhibits the geometry of the problem. The rectangular box has a length of 0.40 m, width of 0.30 m, height of 0.10 m and wall thickness of 10 mm. The inlet nozzle has a hexahedral geometry with length of 30 mm, width of 25 mm and thickness of 2 mm and the outlet nozzle has a cylindrical geometry with diameter of 8 mm and height of 30 mm. The position of the inlet nozzle can be viewed in Fig. 1. The outlet nozzle is placed in the bottom of the mold cavity, centered in the *z* direction and distant 22 m from the left wall of the part (see Fig. 1). A porous medium with isotropic permeability $K = 3.89\times10^{-9}$ m^2 and porosity $\varepsilon = 0.88$ is used, and the resin properties are density $\rho = 916.00$ kg/m^3 and viscosity $\mu = 0.07115$ Pa·s. Besides, to represent the gradient pressure between inlet and outlet nozzles during the LRTM process, an injection pressure of $P = 70$ kPa was considered.

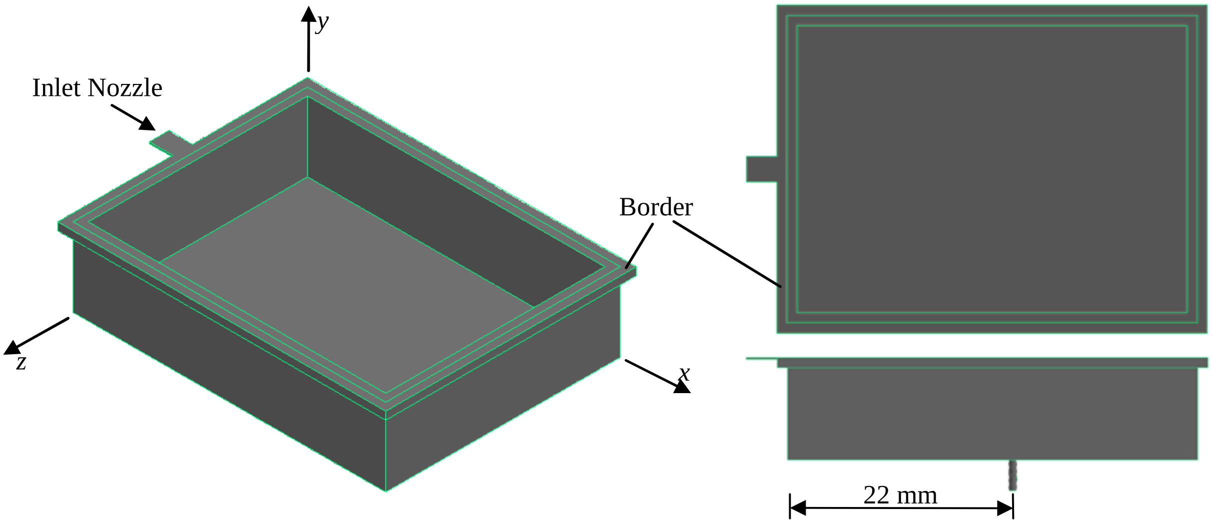

Figure 1. Geometry of the LRTM case studied

To vary the border dimensions was considered the DOF w_b/t_b, i.e., the ratio between the border width (w_b) and the border thickness (t_b). To do so, taking into account the border volume $V_b = 0.148\times10^{-3}$ m^3 and the part volume $V_p = 2.424\times10^{-3}$ m^3, the border volume fraction $\phi = 0.061$ was kept constant and a range of $0.06 \le w_b/t_b \le 9.01$ was investigated, totalizing twelve cases which were numerically analyzed (Fig. 2).

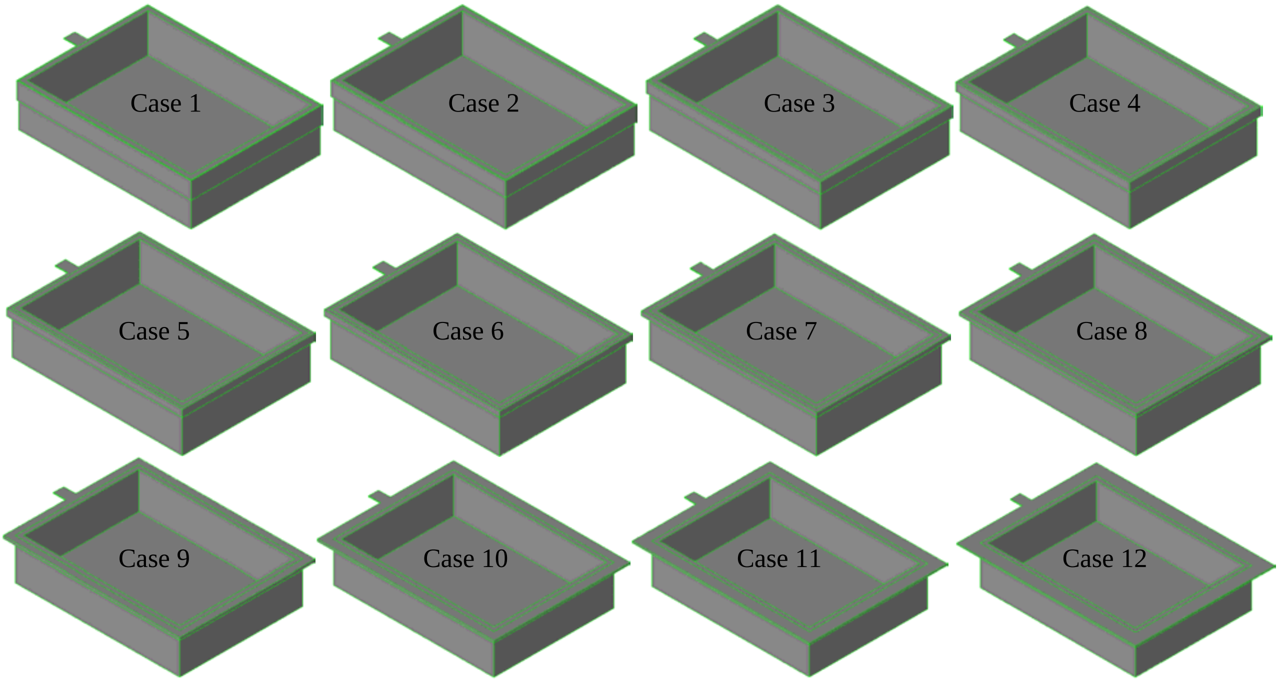

Figure 2. Cases analyzed in the geometric optimization study

The construction and discretization of all geometries presented in Fig. 2 were carried out in GAMBIT software. The domain was discretized with nearly 150,000 tetrahedral finite volumes for each case.

Moreover, the border thickness, width, the ratio between these variables (w_b/t_b) and the total filling time for each case are showed in Tab. 1.

Table 1. Variation of the border dimension and corresponding filling time.

Case	w_b (mm)	t_b (mm)	w_b/t_b	t (s)
1	2.50	40.00	0.06	10.79
2	3.00	33.33	0.09	10.40
3	4.00	25.00	0.16	10.03
4	5.00	20.00	0.25	9.99
5	6.00	16.67	0.36	9.96
6	7.50	13.33	0.56	10.21
7	10.00	10.00	1.00	10.71
8	12.50	8.00	1.56	10.71
9	15.00	6.67	2.25	10.84
10	20.00	5.00	4.00	11.15
11	25.00	4.00	6.25	11.30
12	30.00	3.33	9.01	11.81

Hence, with the results obtained in the numerical simulations (Tab. 1) it was possible to plot a diagram w_b/t_b versus t, allowing the observation the effect of the ratio of w_b/t_b over the mold filling in the LRTM process (Fig. 3).

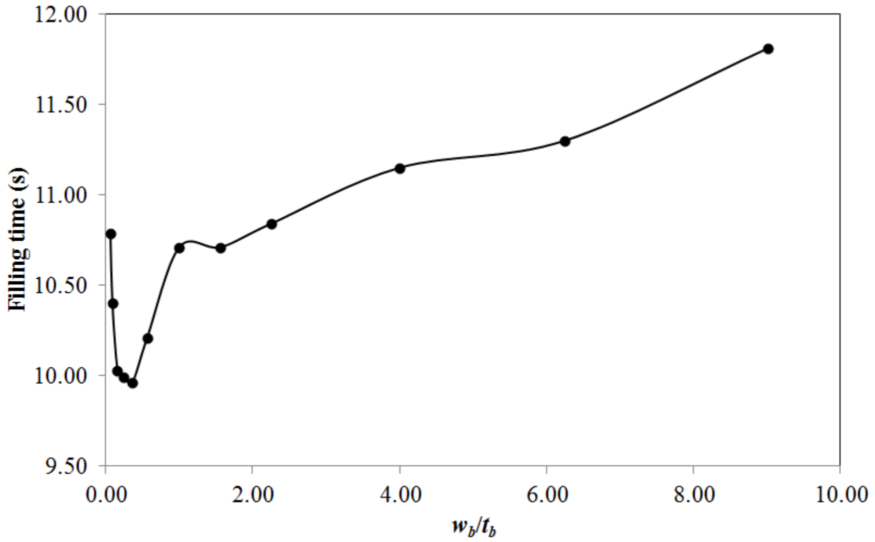

Figure 3. The effect of the ratio w_b/t_b over the filling time.

One can observe in Fig. 3 that there is a well defined minimum filling time, indicating that there is an optimal geometry in the studied LRTM problem. This geometry is defined by Case 5 (Tab. 1) with a optimal ratio of $(w_b/t_b)_o = 0.36$, which leads to a minimal filling time of $t_m = 9.96$ s. Here the subscripts "o" and "m" means once optimized geometry and the once minimized time, respectively. An improvement of 18.57 % was encountered if the optimal case is compared with the worst one (Case 12 with $w_b/t_b = 9.01$ and a filling time of $t = 11.81$ s).

If the pressure fields of Cases 5 and 12 were compared it is possible to observe that the optimal geometry (Case 5) lead to a most uniform pressure distribution (right hand side of Figs. 4 and 5), which is in accordance with the Constructal principle of the "optimal distribution of imperfections". This trend also can be proved if the Figs. 4(d) and 5(d) (on the left hand side) are compared, because it is possible to note that a perfect ellipse is formed in the final of the LRTM process, i.e., the mold filling occur in a better distributed way. Therefore, the best shape will be the one which most facilitates the resin access through the mold cavity, enabling a faster mold filling when the LRTM process is applied to manufacture the studied case - a rectangular box.

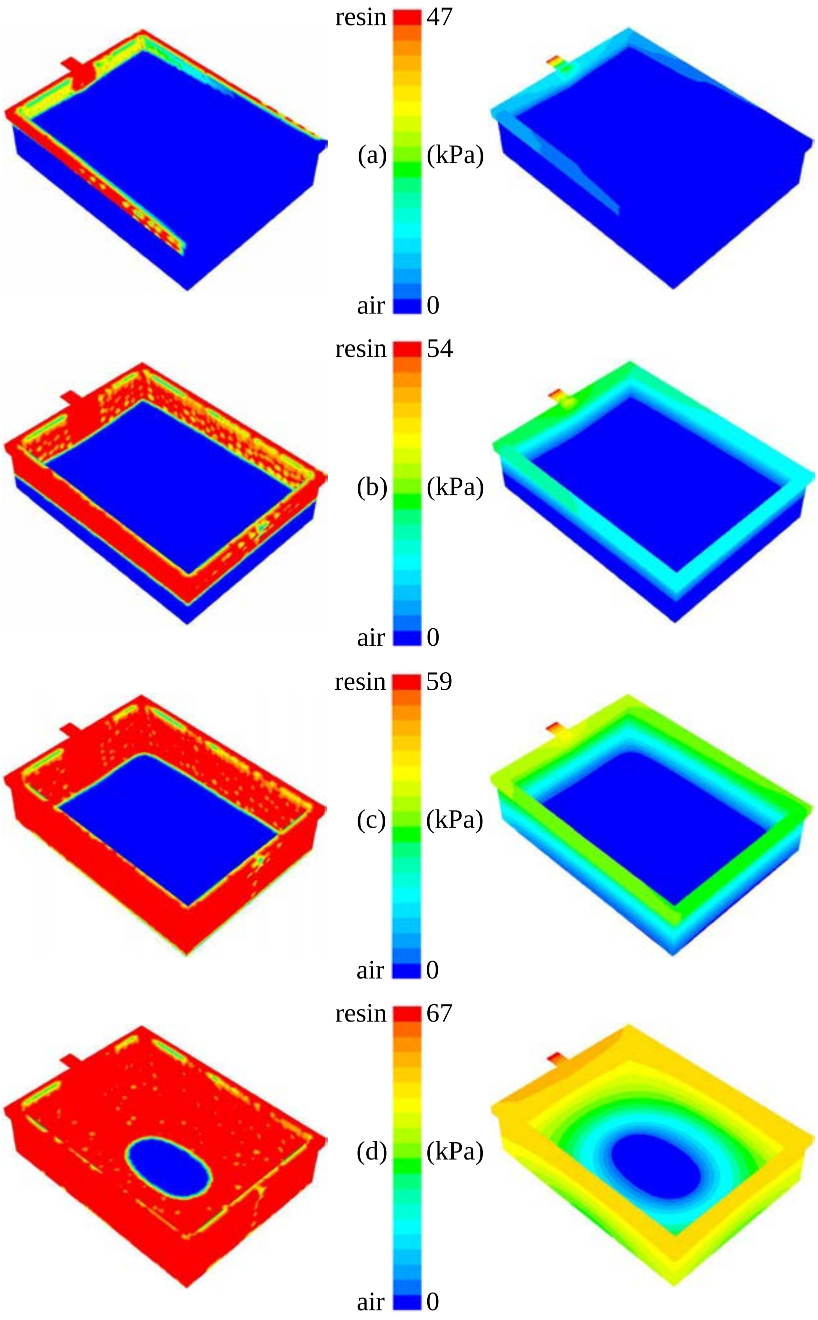

Figure 4. Resin flow front and pressure field for the Case 5 (optimal) at time: (a) t = 0.72 s, (b) t = 2.51 s, (c) t = 4.74 s and (d) t = 8.72 s.

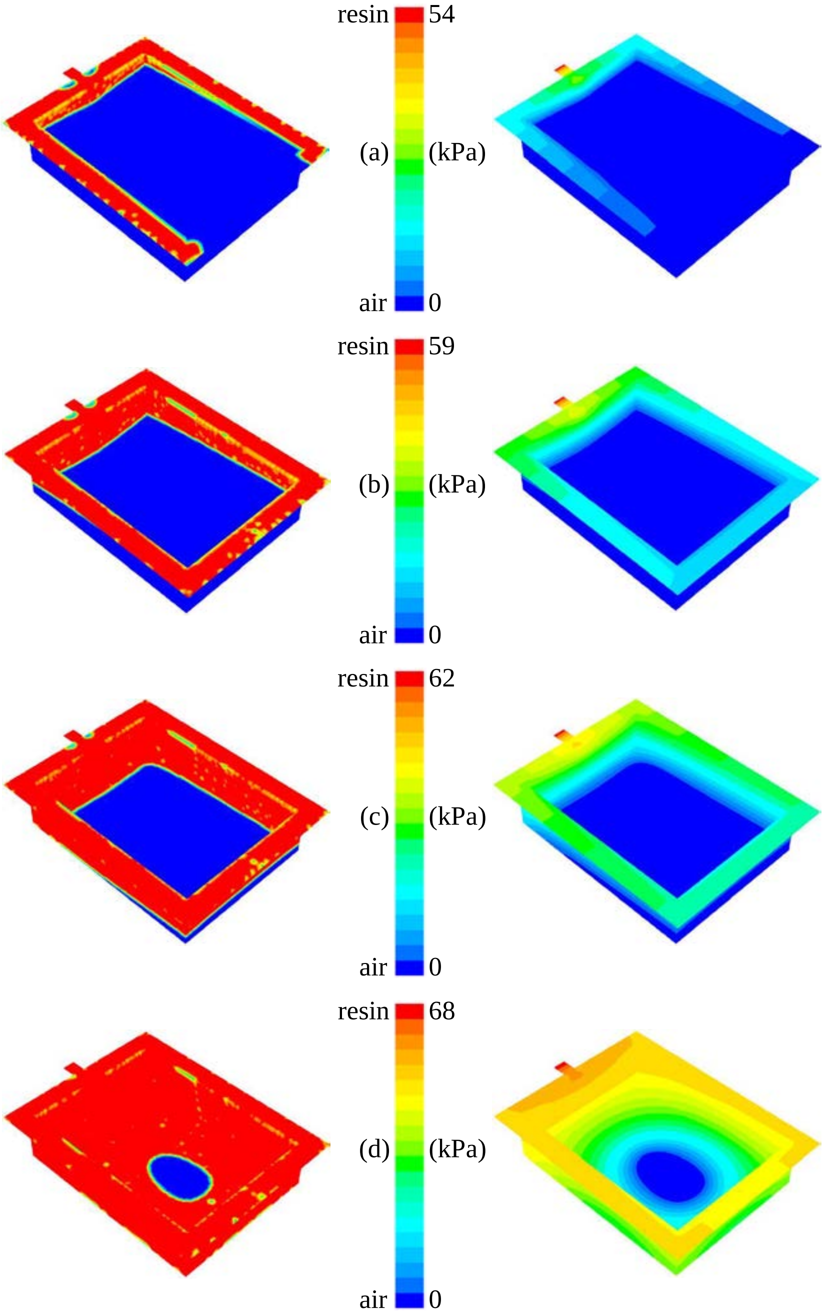

Figure 5. Resin flow front and pressure field for the Case 12 (which leads to the worst performance) at time: (a) t = 0.87 s, (b) t = 2.88 s, (c) t = 5.27 s and (d) t = 10.82 s

Another aspect that can be analyzed is why, theoretically, the optimal shape is not the case with lowest ratio of w_b/t_b (Case 1), since the increase of the border thickness, would allow a greater contact between the border and mold surfaces, hence needing a lower filling time. In Fig. 6 the filling behavior for the Case 1 is depicted.

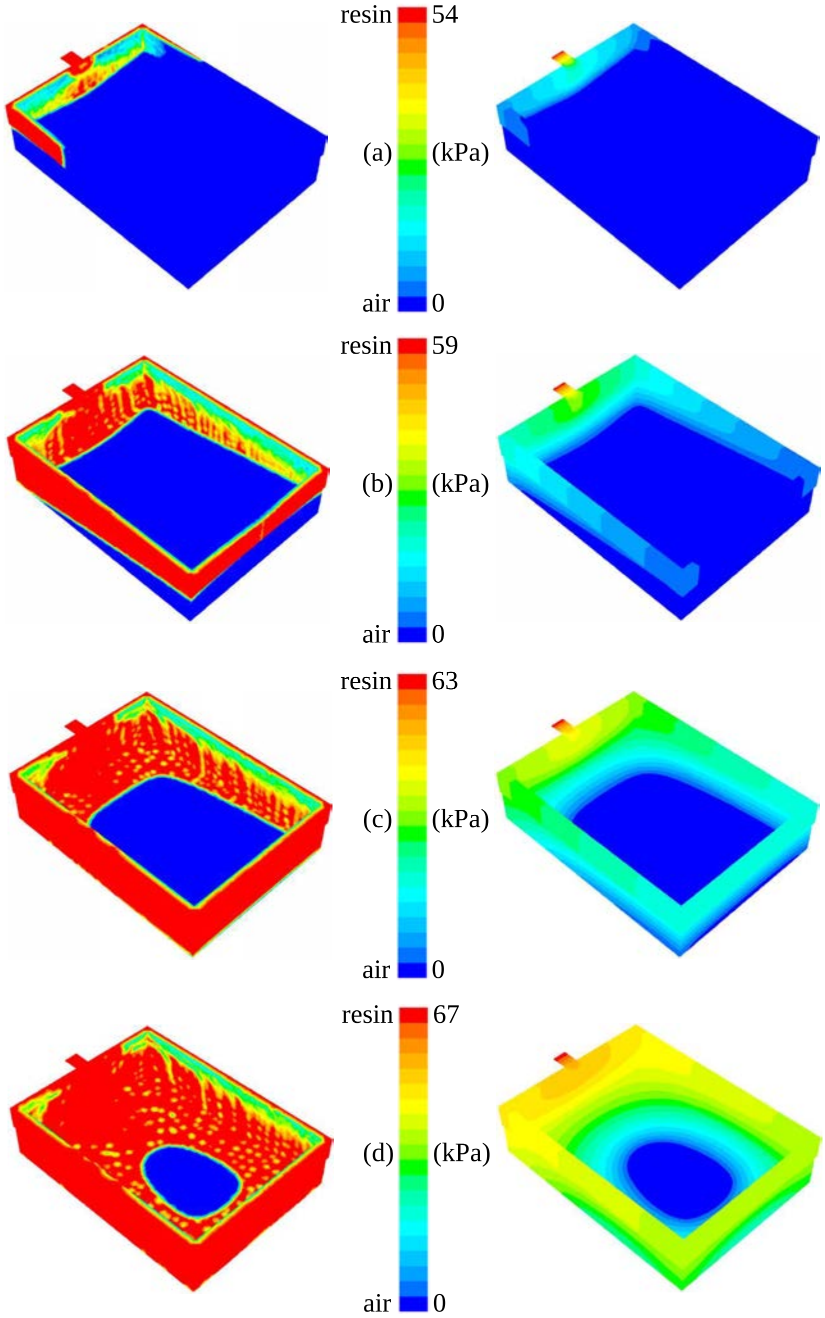

Figure 6. Resin flow front and pressure field for the Case 1 (the lowest ratio of w_b/t_b) at time: (a) t = 0.73 s, (b) t = 3.55 s, (c) t = 6.38 s and (d) t = 9.34 s.

Figure 6 indicates that due to the small value of the ratio w_b/t_b, the resin injection, in practice, crosses the small border thickness and achieves the mold region (which contain the fibrous reinforcement) before of the entire or almost entire border's filling. This behavior makes more difficult the injection of the resin into the mold, because the empty border (without fibrous reinforcement) cannot perform in an optimal way its function of serving as a peripheral channel for injecting the polymeric resin into the mold. Concerning the distribution of pressure field, for Case 1 it is noticed a strong concentration of pressure in the surface of injection nozzle due to the struggle of the resin to flow over the porous media, avoiding the fast occupation of the border without porous medium. In this sense, a poor distribution of pressure field is obtained in comparison with that achieved for the optimal shape (Case 5), i.e., the best shape is reached for the most homogeneous distribution of pressure field.

6. CONCLUSIONS

In this work a computational model of the LRTM process coupled with the Constructal Design method were employed to determine the optimal geometry for the empty channel (border). A border with a rectangular cross sectional area was considered, keeping constant its volume fraction $\phi = V_b/V_p$ (ratio between the border volume and the part volume) while its dimensions varied in accordance with the ratio w_b/t_b. For each value of this DOF (see Tab. 1) a geometry was built and discretized by the GAMBIT software. After that, the LRTM process was numerically simulated with the FLUENT software. The VOF model was employed to reproduce the interaction between the injected polymeric resin and the air existing into the mold. As the objective function of the geometrical optimization was to minimize the filling time, this variable was monitored for all twelve studied cases, aiming to define the optimal border dimensions.

The optimal geometry was obtained for one optimal ratio of $(w_b/t_b)_o = 9.01$, which results in a filling time of $t_m = 9.96$ s (Case 5), while the worst case was defined by $w_b/t_b = 9.01$, which led to a filling time of $t = 11.81$ s (Case 12). Comparing these cases, the best one reached to a filling time almost 20 % faster than the worst case.

Therefore the Constructal Design allowed the definition of a well defined optimal geometry for the injection border in the LRTM process, reached for the best distribution of pressure fields, i.e., in accordance with the Constructal principle of the "optimal distribution of imperfections". Examples of the above mentioned behavior was showed in the transient patterns of resin flow front advance and the pressure field seen in Figs. 4 – 6.

Being the employment of the Constructal Design an original contribution of this work, researches involving other values for the border volume fraction or border shapes as well as parts with other geometries must be investigated in future works.

7. ACKNOWLEDGEMENTS

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