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NUMERICAL ANALYSIS OF CONSTRUCTION OF EMPTY CHANNELS INSERTED IN POROUS MEDIUM PLATE COMPARING TWO DIFFERENT BOUNDARY CONDITIONS

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Abstract. *Present numerical study investigates the construction of empty channels based on Constructal Theory in a porous plate considering two different boundary conditions: external surfaces of the plate with prescribed atmospheric pressure and lateral surfaces with no-slip and impermeability boundary condition. The main purpose is the development of a methodology where the form and structure of the channels growth from an elementary empty channel using a construction function instead of use of predefined shapes for empty channels. The other goal is to investigate the influence of boundary conditions in the channel growth and performance indicators. Conservation equations of mass, momentum and one transport equation of volume fraction of resin are solved with the Finite Volume Method (FVM). The Volume of Fluid (VOF) model is used for the treatment of multiphase flow. Results indicated that the design growth was similar for both boundary conditions. The influence of the number of Constructal elements over the resin infusion time to impregnate the porous plate was similar for both boundary conditions. However, the effect of number of elements over the amount of wasted resin is affected by the boundary condition.*

Keywords: *Numerical analysis, Boundary conditions, Resin infusion, Empty Channels, Constructal Theory.*

1. INTRODUCTION

With the market and technology evolution, the scientists and engineers are always searching for new materials that provide better resistance, lightness and low density. There is a need of advanced materials with a combination of specific properties for improvement of characteristics such as resistance to corrosion, higher mechanical resistance in relation to weight, resistance to higher temperatures and erosion. The composite materials offer the essence to attend many of the required properties (Luo et al., 2001; Poodts et al., 2013).

Liquid Composite Molding (LCM) techniques are innovative and show great potential to produce components with low cost and high quality, as well as, flexible and complex parts. One prominent example of the application of composite materials are seen in aeronautical industry, that have as a challenge the fuel saving. One of strategies to achieve this goal consists on the optimization of density of materials used in the airplane components. The airplanes Airbus A350 and Boeing 787 have more than 50% of their structures built with composite materials. Beyond the aerospace industry, the use of composite materials is increasingly more attractive in the automotive sector, since they offer the possibility of weight reduction in a structure keeping the mechanical properties. Therefore, efficient technologies to the manufacture of high quality Fiber Reinforced Composite parts (FRCP) are an object of growing interest (Grossing et al., 2016).

The injection of resin in the fibrous medium depends on the chosen LCM process, being one of the most important the Liquid Resin Infusion (LRI) which consists on the infusion of a polymeric resin using open channels inserted in a fiber medium domain, which are impregnated with the resin. The empty channels make easier the global propagation of the resin along the mold domain (Wang et al., 2012).

To manufacture a polymeric composite material component with high quality, it is necessary to control the resin flow to avoid dry spots in the component. The presence of empty spaces can considerably damage the mechanical properties of a structure, causing harmful effects, like low resistance to shear stress, compression, impact and fatigue (Grossing et al., 2016; Matsuzaki et al., 2013; Poodts et al., 2013).

In LRI processes, the most important aspects are the efficiency of the resin infusion in terms of infusion time, costs and the quality of the generated parts. In this sense, when a LRI process is configured it is necessary to predict the behavior of the resin flow along the porous domain, being the arrangement of inlets and outlets of resin a critical task. The configuration of empty channels, for example, has a great impact over the resin flow pattern and, as consequence, the mold filling time. In the industrial field, the method of trial and error has been often employed to indicate the better geometrical configurations, which can lead to high infusions time and degrees of failure during the initial stages of the production of a new component made of composite material. Besides that, this iterative procedure is generally costly since it involves human resources, equipment and materials (Grossing et al., 2016; Luo et al., 2001; Matsuzaki et al., 2013; Poodts et al., 2013).

Numerical simulations are promising to reduce trial and error and, therefore, saving resources in conception of LRI process. As a result, it is possible to predict the pressure distribution, resin flow patterns and empty spaces formations. With this information, some parameters of the process can be optimized, e.g., infusion empty channels, locations of resin inlet and outlet, mold filling time, waste of resin or dry regions (Grossing et al., 2016; Luo et al., 2001; Matsuzaki et al., 2013).

Present work proposes the development of a methodology where form and structure of the channels growth from an elementary construction using a function based on the flow resistance. Moreover, it is investigated the influence of two different boundary conditions over the shape of the constructed empty channels, as well as, performance indicators of the system (resin filling time for impregnation in the whole porous domain and the mass of resin that is wasted in the resin infusion process). The algorithm of construction is based on the Constructal Theory. The application of Constructal Theory for generation of empty channels configurations inserted in porous medium has not been explored in the literature.

According to Bejan (2000), Constructal Theory is a mental viewing that the design of all flow systems of finite size is ruled by a physical principle of design and evolution along the time (Constructal Law). Constructal Law states that for the finite size flow system to persist alive its design must evolve to facilitate the access of internal currents in the system (Bejan, 2016, 2018; Bejan and Lorente, 2008).

In the present numerical work, resin flow advancement is modeled with the conservation equations of mass, momentum and one transport equation for volume fraction of resin. These equations are solved with the Finite Volume Method (FVM). To deal with the mixture resin/air flow, the Volume of Fluid (VOF) method is used. In the region of the porous medium, it is considered the employment of a body force modeled with the Darcy's law. More precisely, the simulations are made using the Computational Fluid Dynamics (CFD) code FLUENT, version 14 (ANSYS, 2013).

2. MATEMATICAL AND NUMERICAL MODELING

In the present study, it is considered an incompressible, laminar, and transient flow of a resin/air mixture in a two-dimensional domain. Moreover, the two phases are treated as immiscible. For the prediction of this kind of flow, it is numerically solved the conservation equations of mass and momentum for the mixture resin/air and one transport equation for prediction of resin volume fraction. The conservation equations of mass and momentum for the resin/air mixture are given by (Schlichting, 1979):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla \cdot (\rho \mathbf{V}\mathbf{V}) = -\nabla P + \nabla \cdot \boldsymbol{\tau} + \mathbf{F} \tag{2}$$

where ρ is the mixture density (kg/m³), $\mathbf{V}$ is the velocity vector (m/s), t is the time (s), μ is the dynamic viscosity of the fluid (Pa.s), ∇P is the pressure gradient (Pa/m), $\vec{F}$ is an external force vector per unit volume (N/m³) and $\boldsymbol{\tau}$ is the stress tensor of the fluid (N/m²), given by:

$$\boldsymbol{\tau} = \mu\left(\nabla \mathbf{V} + \nabla \mathbf{V}^T\right) \tag{3}$$

The effect of the porous medium is included in the mathematical model by the insertion of a body force in the momentum equation based on Darcy's law, as given by (Morren et al., 2009; Rudd et al., 1997; Schlichting, 1979):

$$\mathbf{F} = -\mu \left[\mathbf{K}\right]^{-1} \cdot \mathbf{V} \tag{4}$$

where $\mathbf{K}$ is the permeability coefficient of the porous medium [m²].

To tackle with the mixture of resin/air, it is employed the Volume of Fluid (VOF) method (Hirt & Nichols, 1981). In this approach, an additional transport equation for resin volume fraction (f) is necessary to define the quantity of resin along with each cell of the domain. This transport equation is given by (Hirt and Nichols, 1981):

$$\frac{\partial f}{\partial t} + \nabla \cdot \left(f\mathbf{V} \right) = 0 \tag{5}$$

With the definition of the volume fraction, density, and dynamic viscosity in each cell of the computational domain can be calculated by (Srinivasan *et al.*, 2011):

$$\rho = f\rho + (1 - f)\rho \tag{6}$$

$$\mu = f\mu + (1 - f)\mu \tag{7}$$

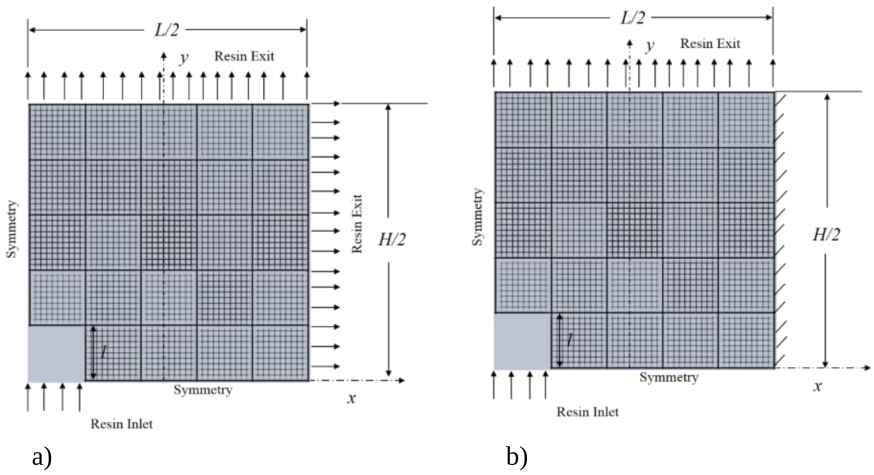
Concerning the thermophysical properties, it is considered densities of ρ_{res} = 916 kg/m³ and ρ_{air} = 1.225 kg/m³ and dynamic viscosities of μ_{res} = 0.06 Pa.s and μ_{air} = 1.7894 × 10^{-5} kg/(ms). For the porous medium, it is considered a permeability of $\mathbf{K} = 2.0\times10^{-11}$ m² and porosity of $\varepsilon = 0.50$. These properties have been previously used in literature, see Trindade et al. (2019).

2.1 Description of the problem

The problem consists on a resin flow considered incompressible, transient, laminar in a two dimensional domain. Present problem consists on the insertion of empty channels inserted along one rectangular plate with porous medium, mimicking a LRI process. Main purpose of the employment of empty channels is to ease the resin impregnation in the porous mold.

Resin flow is generated by the imposition of pressure difference between the resin inlet (inferior region of the channel) and the exit regions, as can be seen in Fig. 1. Figure 1 illustrates one fourth of a porous plate simulated here with the inlet of resin being performed in the central region of the domain. Two different cases are simulated considering different fluid flow boundary conditions: 1) the right and upper surfaces have null gauge pressure imposed, Fig. 1(a), and 2) the upper surface has a null gauge pressure imposed in the upper surface and no-slip and impermeability boundary condition in the right lateral surface, Fig. 1(b). For both cases, a pressure inlet of $P_{in} = 1 \times 10^5$ Pa is imposed in the lower left surface of the domain, while symmetry boundary condition in the remaining surfaces.

For the resin volume fraction, f = 1 is prescribed at the inlet section and $\partial f / \partial n$ is set to all other computational boundaries (n is the normal to the boundary direction).



a) b)

Figure 1 – Illustration of the computational domain of the LRI being simulated with different boundary conditions: a) mold without walls, b) mold with lateral walls.

2.2 Building of the empty channels with Constructal Theory

For construction of the geometry of empty channels with Constructal Theory, firstly the performance indicators of the system are defined. Here, two performance indicators are analyzed: the filling time of impregnation of the resin in the whole domain and the wasted amount of mass of resin necessary to impregnate the whole domain. The best shapes are the ones that minimize these performance indicators. The growth of empty channels from an elementary construction is performed with the use of a construction function, in such way to provide the lowest resistance to the resin flow. Here, it is not used a pre-defined configuration for the empty channel. It is also established the operational parameters and the problem geometrical constraints.

Present problem is subject to two constraints, the total domain area:

$$A = HL \tag{8}$$

and the fraction area of the empty channel (ratio between the open channel and the plate areas), which is given as:

$$\phi = \frac{A_0}{A} \tag{9}$$

where A is the total area of the porous plate [m²], H is the porous plate height [m], L is the porous plate length [m], A_0 is the area of the empty channel [m].

The proposed methodology can be seen schematically in Fig. 1. The plate domain is shared in several imaginary small squares where empty channels can be mounted. These regions do not have relation with the spatial discretization for solution of the fluid flow with the CFD code. The construction starts with an elementary empty channel (N = 1) placed in the lower and left region of the plate domain (see light gray region in Fig. 1). Each element mounted in the domain is called here “Elemental Constructal” (EC). The dimensions of ECs are important for generation of the empty channels design and it is called here “Channel Resolution” (CR). The number of mounted ECs and the size of CRs are the degrees of freedom of the present problem. Here, it is considered the same number of possible positions in x and y directions for mounting of new ECs and a constant magnitude of CR. As higher is the CR, smaller is the area of each EC, resulting in a larger number of possible configurations for mounting of the final configuration of empty channel (Vianna *et al.*, 2018). A superior limit for fraction area of the constructed empty channel is also defined to limit the occupation of the empty channel in the porous plate.

After the definition of the first case with the elementary empty channel, it is performed the numerical simulation to find fluid dynamic fields, as well as, the performance indicators. Then, the flow resistance is calculated in the adjacent square domains where a new EC can be mounted. The region with the lowest resistance is chosen to be the position where a new empty channel EC is mounted. Then, the region with smaller flow resistance is change from a porous medium element to an empty channel element, leading to a growth of the empty channel. As a posterior step, the new domain is defined, a new simulation is performed and the fluid dynamic field is calculated. From this field, the flow resistance is calculated for the new configuration and other position for insertion of new empty channel is defined. This procedure is repeated up to the empty channel reaches a maximum fraction area (ϕ_{max}). Here, the growth process can be stopped when the new generated empty channel led to permanent void formations in the plate. Moreover, in the present work only one element is mounted per growth step. For each growth step, the performance indicators (filling time and mass of resin wasted) are calculated to investigate how it is affected by the empty channels design.

For the present study, the plate is shared in 121 square regions, being one initially occupied with empty channel. Each new EC can be mounted up to a maximum fraction area of ϕ_{max} = 0.2. Therefore, at each step of growth, the channel area increases 1/25 its magnitude in comparison with the first case of elementary construction (since it is considered a symmetry condition of the mold and it is simulated only one forth of the domain). Here, it is necessary five steps for construction of the resin infusion channel considering the maximum fraction area, which indicates a course resolution imposed for the present problem.

Flow resistance is defined as the ratio between two adjacent ECs pressure drop (potential difference) and the mass flow rate, as given by (Errera and Bejan, 1998):

$$R = \frac{\Delta P}{\rho V l W} \tag{10}$$

where ΔP is the pressure drop between two adjacent ECs regions [Pa], ρ is the mixture density (kg/m³), V is velocity in the center of regions where a new EC can be mounted [m/s], l is the size of EC crossed by the resin [m] and W is the dimension in the z plane, which in the present work is treated as unitary since the domain is two-dimensional.

2.3 Numerical Procedures and Spatial Discretization

For the numerical simulation of Eqs. (1) – (5) the Finite Volume Method (FVM) is used (Patankar, 1980; Versteeg and Malalasekera, 2007). More precisely, it is employed the commercial code FLUENT, version 14 (ANSYS, 2013). The pressure interpolation is made using the PRESTO (*PREssure STaggering Option*) scheme. The coupling pressure-velocity is made by PISO method, while the Geo-Reconstruction is used to solve the volume fraction. Simulations are performed in a computer with two Intel dual-core processors with 2.67 GHz and 8 GB of RAM memory. Simulations are considered converged when the residuals are lower than $R < 10^{-6}$. For the time discretization, it is applied a variable time step in the range $\Delta t = 1{,}0\times10^{-3}$ s to $\Delta t = 1.0$ s. Concerning the spatial discretization, the domain is divided in several rectangular finite volumes and a mesh independence test is done to define the number of volumes used in all simulations.

The created mesh is regular, with rectangular volumes, and each EC is discretized with $n_R \times n_R$ finite volumes, where n_R is the division of an EC in the rectangular finite volumes. Table 1 shows the number of divisions in each EC (n_R), the number of volumes of discretization of the whole domain, the injection time for the mold filling and the difference between two successive solutions (discretizations). The chosen problem to check the mesh independence was the case with no-slip and impermeability boundary condition in lateral surface and only one EC with empty channel (N = 1). The grid is considered independent when the relative difference between the infusion time obtained with two successive grids comply with a mesh refinement criterion, which is given by:

$$\textit{Relative difference} = \frac{100\left(t^{j} - t^{j+1}\right)}{t^{j}} < 0.5\% \tag{11}$$

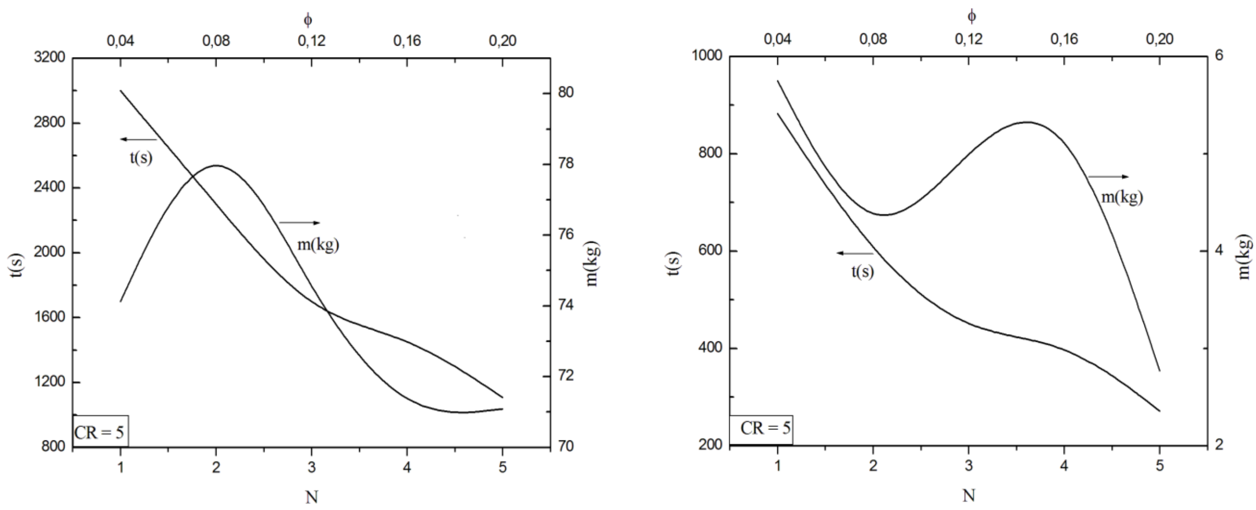
where t^j represent the lowest injection time value calculated with the coarsest mesh and t^{j+1} correspond to the calculated value with a refined mesh. Besides the criterion described in Eq. (11) it is analyzed the mold filling quality. For the cases with $n_R < 8$ it is noticed the generation of permanent voids leading to disregarding of these cases once the generation of empty spaces is a critical problem in the LRI process. In this sense, it is chosen a grid with 2,500 finite volumes as the independent grid.

Table 1 - Test of mesh independence for the case with walls in the lateral surfaces and N = 1.

n_R	Number of Volumes	Infusion Time (s)	Difference (%)
2	100	895.78	1.23
4	400	884.78	0.23
6	900	882.78	0.14
8	1,600	881.55	0.18
10	2,500	883.189	0.029
12	3,600	883.447	-----

3. RESULTS AND DISCUSSION

Figure 2 illustrates the effect of the number of inserted empty channels over the filling time for impregnation of the resin in the porous domain (t) and the amount of resin mass wasted in the process (m). The elementary construction have one EC (N = 1), and the maximum number of ECs is limited by ϕ_{max}. The quantity of ECs that reach the maximum area rate is five (N = 5). Figure 2(a) shows the investigation for the case with atmospheric pressure in lateral surface and Fig. 2(b) presents the results for the case with no-slip and impermeability boundary condition in the lateral surface. For the obtained results, it is possible to notice that for the mold without lateral walls, the infusion time (t) and the wasted mass of resin (m) in the process have higher magnitudes than for the case with lateral walls. For both cases, it can be noticed that the highest number of empty channels (N = 5) leads to the best performance, regardless of the performance indicator investigated (t or m). Concerning the effect of number of ECs (or the magnitude of ϕ) over the performance indicators, in spite of different magnitudes, the different boundary conditions do not affected the behavior of the filling time (t). On the opposite, the effect of N or ϕ over m changes for different imposed boundary conditions, which is expected since the influence of neighboring on the flow system is also different. In Fig. 2(a), for the case without lateral walls, an increase of m in the first step is noticed followed by a decrease of m from N = 2 to N = 4, and a stabilization of m for $N \geq 4$. For the most elemental configuration, it is also noticed a local minimum of wasted mass of resin. For the case of Fig. 2(b), porous plate with lateral walls, the pattern of m as a function of N changes and the second construction (N = 2) became the local optimum. Moreover, a strong decrease is seen in m from N = 4 to N = 5, contrarily to what is noticed for the other boundary condition. Therefore, results indicated that the boundary condition was important for definition of the effect of the empty channel growth over the wasted mass of resin (m) in the process. One possible explanation for the achievement of the lowest magnitude of m for N = 5 can be related with the fast conclusion of the process.



a) b)

Figure 2 – Effect of the number of ECs and the ϕ ratio along the infusion time and waste of resin mass (m): a) mold without lateral walls, b) mold with walls in lateral surfaces.

Figure 3 illustrates the advance of resin front line into the porous mold for the best configurations found in Fig. 2 (N = 5 or ϕ = 0.2). More precisely, Figs. 3(a) and 3(b) show respectively the optimal shape for the case without lateral walls and for the case with lateral wall, respectively, for two different instants of time (t = 90.0 s and 190.0 s). The red region represents the resin (f = 1.0) and blue region represents the air (f = 0) while other colors (yellow and green) represent intermediate volume fractions with a mixture between air and resin ($0.0 < f < 1.0$).

In Figure 3 it can be observed that, for different boundary conditions, the resin spread in almost radial pattern, independent of the boundary condition. The sole difference is the direction where the resin advances with higher velocity, in y direction for the case without lateral wall and x direction for the case with lateral wall. Results also indicated that there is no important void generated in the porous domain, which would inviable the production of the piece. For the mold with lateral wall, Fig. 3(b), when t = 190.0 s it is possible to observe the generation of permanent small voids near the lateral surface. This generation is caused by the shear stress in the front line of resin retaining some air in the resin. In spite of this fact, this kind of design can be considered valid since the piece can receive a final finish (like applying sanding at the surface) preventing any damage to the final component.

Figure 4 shows the geometry configurations at each step of empty channel growth, since the most important aspect in this work is the construction of the empty channel from several ECs. Results indicated that the first four steps led to the same geometrical configurations, with a kind of rectangle for N = 1, 2 and 4 and H-shaped channel for N = 3 and 5. For the last step, it can be seen a growth of new branches of H-shaped channel in different directions. In spite of limited analysis, results indicated that this methodology can be an alternative for design of empty channels inserted in porous media, mainly when a predefined configuration suitable for the problem is unknown. Results also indicated highly different performance comparing the best and worst shapes. It is worthy to mention that the resolution of the empty channels is too coarse, i.e., its size has a large dimension. Therefore, more refined ECs should be investigated in future studies. Perhaps, the construction of empty channels can be strongly affected by the resolution of the ECs.

4. CONCLUSIONS

In the present numerical work, construction of empty channels based on Constructal Theory was performed. Two different boundary conditions were imposed to investigate its influence over the construction of empty channels domain. Moreover, two different performance indicators were investigated (resin infusion filling time and wasted resin mass in the process). The main purpose was to develop a method for construction of the channels from an elementary construction and mounting each Elemental Constructal (EC) based on a construction function, which can be more similar to construction ways found in natural systems. Conservation equations of mass, momentum and transport equation of volume fraction were solved with the Finite Volume Method (FVM). To tackle with the multiphase flow, it was employed the Volume of Fluid (VOF) method.

Results showed that the methodology of growth of empty channels from an elementary construction using Constructal Theory can be a promising technique for generation of design in this kind of problem, mainly when a suitable predefined shape is unknown. For both boundary conditions investigated, the most complex configurations (with N = 5 inserted empty channels) led to the best performance for reduction of infusion filling time (t) and the wasted mass of resin (m). The performance difference between the best and worst shapes were significant, regardless of performance indicator considered. Moreover, the effect of N over t was quite similar for both boundary conditions, while the effect of N over wasted resin mass (m) changed for different boundary conditions, showing the importance of case definition and choice of performance indicator for generation of design. Results also demonstrated that the use of lateral walls decrease significantly the filling time and wasted mass of resin, being recommended for future studies.

In spite of first promising results, future studies should be performed to refine the number of ECs used in the construction, investigate the influence of CR over the generated design, as well as, test other conditions of growth as mounting two ECs at each step.

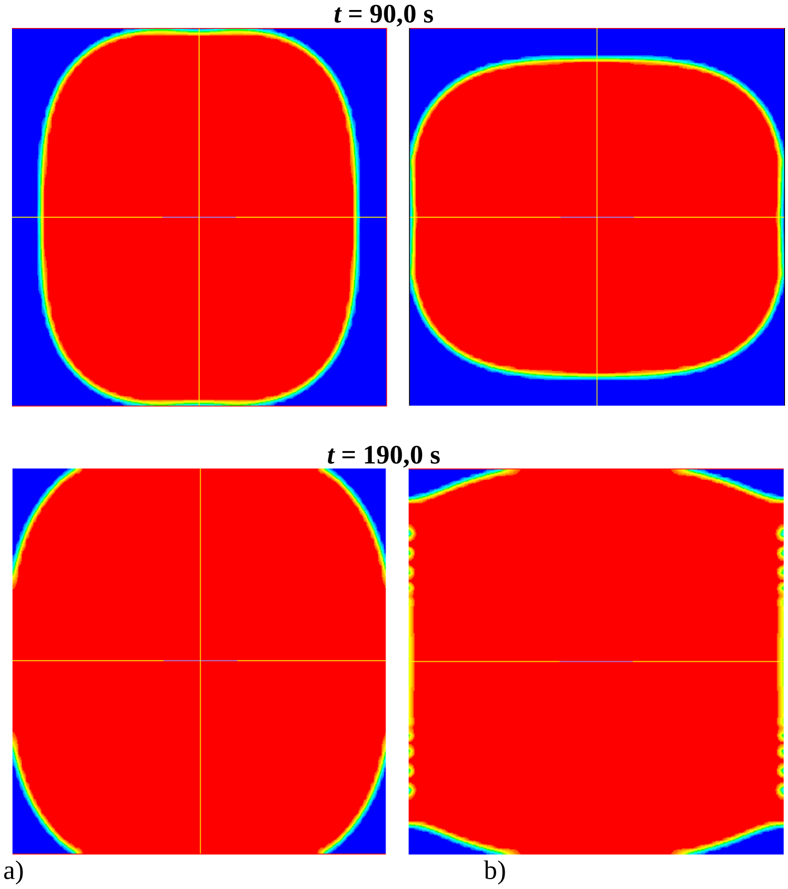


Figure 3 – Resin volume fraction as a function of time for N = 5 and ϕ = 0.2 with two different boundary conditions: a) mold without lateral wall, b) mold with wall in lateral surfaces.

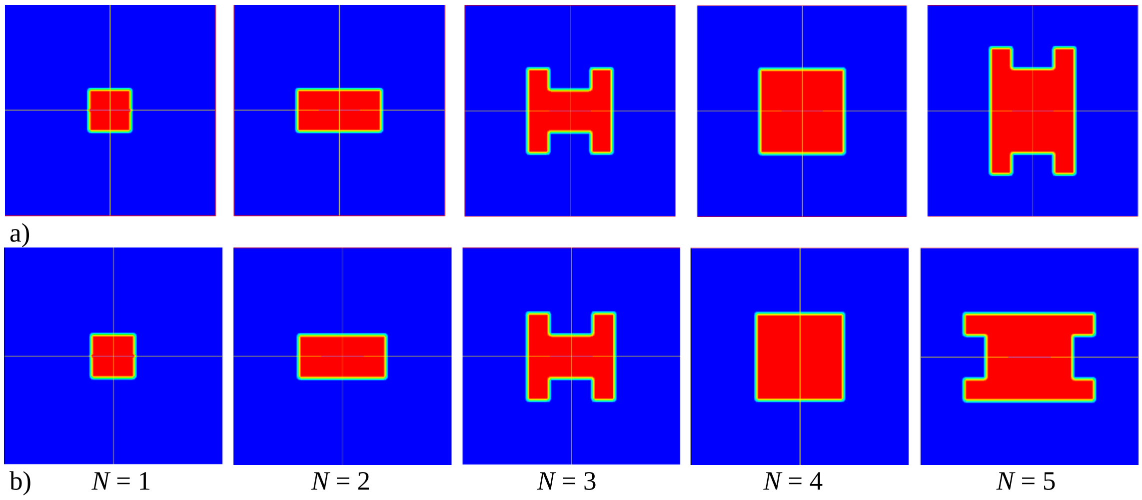


Figure 4 – Scheme of the ECs assembly for the both studied cases: a) mold without walls, b) mold with wall in lateral surfaces.

5. ACKNOWLEDGEMENTS

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