A ROBUST PROCESS MODEL WITH TWO-STAGE OPTIMIZATION METHODOLOGY FOR LIQUID COMPOSITE MOLDING PROCESS

by

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ABSTRACT

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Liquid Composite Molding (LCM) is the family of the advanced composite manufacturing method in which dry preform is placed into the mold cavity followed by filling of the preform with the resin system. The final composite part is obtained after the curing cycle. The success of the final part for LCM highly relies on the success of the impregnation of the resin system through the dry preform. In order to have fully impregnated domain, the inlet and vent locations, namely gates, should be engineered in such a way that as the resin is introduced through the inlet gate, vent should be placed where the resin arrives last. Otherwise, the process fails with the formation voids/dry spots beyond tolerance values. Additionally, the fill time of the preform domain for complete impregnation should be reduced considering both finalization of the impregnation before gelation time of the resin and the achievement of high production rates. Thus, the LCM process can be improved through the minimization of the two afore-mentioned parameters: void content and fill time. To achieve that one has to predict the flow patterns within the preform.

Mathematical modeling of the resin flow in LCM process is described reasonably well as flow through porous media using Darcy's Law coupled with the continuity equation. Darcy's Law, which relates the resin pressure gradient with the resin velocity, requires

two material properties: permeability tensor of the preform and the resin viscosity. Permeability tensor is a preform property and indicates the ease of flow through the preform. Generally, for the LCM models the permeability value is assigned as a bulk property, with the assumption of uniformity of the fibrous domain. This generates simple, deterministic model but as any material property variations, geometrical variations and lay-up of the assembly generate variations in permeability values, there will be some differences between real and predicted flow patterns. Another source of these differences stems from open channels (gaps) created between the edges and corners of the mold and/or inserts and preform. These ‘race-tracking’ channels have significant effect on the flow patterns which might cause formation of voids. The other property affecting the flow patterns, viscosity, reflects the resistance of the flow of the resin system through the preform and shows variations with temperature and time. The differences between predicted and actual values caused by over-idealized modeling negatively influence any actual utility of model predictions, particularly optimization. Therefore, the accuracy of the model entails accurate permeability data with race-tracking possibilities and viscosity as a function of time and temperature. Note that at this point this is no longer deterministic model.

In this study, a new LCM modeling and optimization approach is introduced which aims to optimize void content and fill time using more realistic permeability and viscosity parameters. This is achieved by a two-stage optimization approach. In the first stage, the inlet and vent location optimization are implemented with Genetic Algorithm (GA) adaptation. The GA adaptation including the permeability variations in terms of race-tracking possibilities identifies the optimal inlet/s and vent/s locations working for all possible race-tracking possibilities with equal occurrence probabilities. Also, the GA adaptation enables further decrease in fill time with multiple inlet and multiple vent optimization practices. Then, in the second stage, using the gate locations from first stage the fill time and void percentage is further improved by placing a tailored highly permeable layer (distribution media, DM). This stage includes the lay-out design of the DM layer using a Discrete Optimization algorithm which dictates successful impregnation with minimum void percent and minimum fill time for all possible flow disturbances due to race-tracking issue. Then, this methodology is validated numerically by using Liquid Injection Molding Simulation (LIMS) for various complex geometries under different constraints. For the resin system the viscosity function is adapted from a commercially available epoxy system and permeability variation is defined as race-tracking channels with very high permeability values at the edges. Additionally, with the use of two-stage optimization methodology, computational time is decreased due to simplifications in objective function definitions.

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ÖZET

SIVI KOMPOZİT KALIPLAMA YÖNTEMİ İÇİN İKİ AŞAMALI OPTİMİZASYON METOTOLOJİSİ İLE GÜÇLENDİRİLMİŞ BİR SÜREÇ MODELİ

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Üretim Mühendisliği, Master Tezi, August 2020

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Sıvı Kompozit Kalıplama Yöntemi (Liquid Composite Molding, LCM) ön şekillendirilmiş kuru kumaşın (dry preform) kalıp boşluğuna yerleştirildiği ve ardından kuru kumaşın reçine sistemi ile doldurulduğu gelişmiş kompozit üretim yöntemi ailesidir. LCM için son parçanın başarısı büyük ölçüde reçine sisteminin kuru kumaşı ıslatabilme başarısına bağlıdır. Bu başarı için, reçine giriş ve hava çıkış yerleri, yani kapıların yerleşimi büyük önem taşımaktadır. Aksi takdirde, tolerans değerlerinin ötesinde oluşan hava boşlukları ve kuru noktalar ile üretim başarısız olur. Ek olarak, bu başarının düşük dolum zamanlarında elde edilmesi gerekmektedir. Böylece, LCM işlemi, boşluk içeriği ve dolum süresinin en aza indirilmesi yoluyla geliştirilebilir.

LCM sürecindeki reçine akışının matematiksel modellemesi, kütle korunumu ve Darcy Kanunu ile çözülen gözenekli ortam akışı ile gerçekleşmektedir. Reçine basınç gradyanını reçine hızı ile ilişkilendiren Darcy Kanunu, iki malzeme özelliği gerektirir: kuru kumaşın geçirgenlik tensörü ve reçine viskozitesi. Geçirgenlik tensörü bir preform özelliğidir ve preform boyunca akış kolaylığını gösterir. Genel olarak, LCM modelleri için, geçirgenlik değeri, kumaş için homojenite varsayımıyla sabit değerler olarak tanımlanır. Ancak, kalıbın veya eklerin ve kumaşın kenarları ve köşeleri arasında oluşturulan açık kanallardan (race-tracking channels) geçirgenlikte farklılıklar oluşmaktadır. Akış modellerini etkileyen diğer bir özellik olan viskozite, reçine

sisteminin preform boyunca akışının direncini yansıtır ve sıcaklık ve zamanla değişimler gösterir. İdeal LCM modellemenin neden olduğu tahmin edilen ve gerçek değerler arasındaki farklar, model tahminlerinin gerçek faydasını, özellikle de optimizasyonu olumsuz yönde etkiler. Bu nedenle, modelin doğruluğu, zaman ve sıcaklığın bir fonksiyonu olarak yarış izleme olanakları ve viskozite ile doğru geçirgenlik verilerini gerektirir.

Bu çalışmada, daha gerçekçi geçirgenlik ve viskozite parametreleri kullanarak boşluk içeriğini ve dolum süresini optimize etmeyi amaçlayan yeni bir LCM modelleme ve optimizasyon yaklaşımı sunulmaktadır. İki aşamalı bir optimizasyon yaklaşımı sunan bu çalışmada, ilk aşamada giriş ve çıkış lokasyonu optimizasyonu Genetik Algoritma (GA) adaptasyonu ile gerçekleştirilmiştir. Açık kanal oluşma olasılıkları açısından geçirgenlik varyasyonlarını içeren GA uyarlaması, eşit oluş olasılıkları ile tüm olası açık kanal olasılıkları için çalışan optimum giriş ve çıkış konumlarını tanımlamaktadır. Ayrıca, GA adaptasyonu, çoklu giriş ve çoklu çıkış optimizasyon uygulamaları ile dolum süresinin daha da azaltılmasını sağlar. Daha sonra, ikinci aşamada, birinci aşamadaki kapı konumlarının kullanılarak, dolum süresi ve boşluk yüzdesi, özel olarak tasarlanmış yüksek geçirgen bir katman (distribution media, DM) yerleştirilerek daha da iyileştirilmiştir. Bu aşama, açık kanal sorunundan kaynaklanan tüm olası akış bozuklukları için minimum boşluk yüzdesi ve minimum dolum süresi ile başarısını Ayrık Optimizasyon algoritması ile DM katmanının yerleşim tasarımını içermektedir. Daha sonra bu metodoloji, farklı kısıtlamalar altında çeşitli karmaşık geometriler için Sıvı Enjeksiyon Kalıplama Simülasyonu (LIMS) kullanılarak sayısal olarak doğrulanmıştır. Reçine sistemi için viskozite değişimi ticari olarak temin edilebilen bir epoksi sisteminden elde edilmiştir. Geçirgenlik değişimi, kenarlarda çok yüksek geçirgenlik değerlerine sahip açık kanallara olarak tanımlanmıştır. Ek olarak, iki aşamalı optimizasyon metodolojisinin kullanılmasıyla, amaç fonksiyonu tanımlarındaki basitleştirmeler nedeniyle hesaplama süresi düşürülmüştür.

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To my lovely sister Mahnaz…

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LIST OF ABBREVIATIONS

LCM	Liquid Composite Molding
RTM	Resin Transfer Molding
VARTM	Vacuum Assisted Resin Transfer Molding
SCRIMP	Seeman Corporation Resin Infusion Molding Process
TPR	Thermoplastic Resin
TSR	Thermoset Resin
GA	Genetic Algorithm
FPS	Fitness-Proportionate selection
OBS	Ordinal based selection
DM	Distribution Media

1 INTRODUCTION

1.1 Polymer Composites

Polymer composites are the integration of two or more distinct materials in a way that the mechanical properties of the achieved part cannot be achieved by any of the materials alone. Polymer composites have the advantage of being stiff and lightweight which make them the common source for many applications (aerospace, automobile, infrastructure, sports and marine). As it is represented in Figure 1.1 polymer composite constituents are polymeric resin or matrix phase of the composite and the fibers [1].

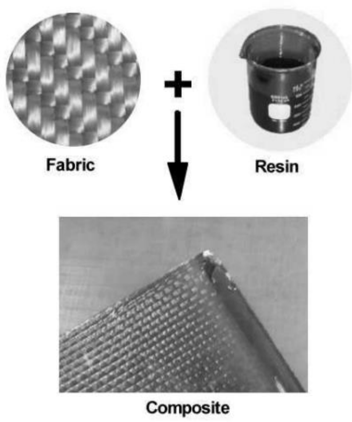

Figure 1.1. Polymer composite and its constituent

Among the various types of fiber carbons, fiber glass and carbon fibers are the most common fibers, however, Aramid and Boron fibers are other types of fibers used in composite materials. Fiber reinforced composites have the advantage of high strength and stiffness comparing to other composite materials. It is shown in Figure 1.2 that composite materials can be classified to three main group according to the fibers orientation: i) continuous fibers ii) discontinuous and aligned fibers and iii) discontinuous and randomly oriented fibers. Continuous or long fibers presented in polymer matrix in forms of unidirectional or bidirectional fibers. On the other hand, discontinuous or short fibers introduced to the matrix in oriented or random forms. Continuous fibers may combine in different types to form fabric preforms. Different fabrication methods like weaving, braiding, knitting, or stitching may adopted to continuous fibers to form fiber reinforcement to be embedded in the matrix [2, 3]**.**

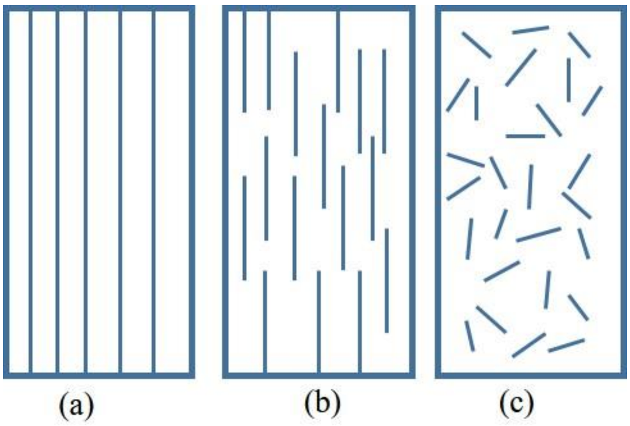

Figure 1.2. Classification of fiber reinforced composites according to the fiber orientation: (a) continuous and aligned fibers (b) discontinuous and aligned fibers (c) discontinuous and randomly oriented fibers

As the other constituent of composite material, Polymer resins may be classified to two main groups of thermoplastics and thermosets. One of the main differences between thermoplastic and thermoset resins is the viscosity range, thermoplastics have much higher viscosity about 10^4 -10^6 times bigger viscosity range comparing to thermosets [1]. Thus, complete penetration of thermoset resin due to low viscosity of resin can be achieved even in room temperature which ensures the mechanical stability of the final composite part. Also, they provide better thermal stability which limits the deformations due to temperature changes to make them a more reliable polymer solution for high-temperature applications such as on electronics. On the other hand, one of the concerns for thermoset resins is they cannot be reshaped or demolded.

Additionally, thermosets require an additional step of curing. Curing step is defined as chemical reactions which result in cross-linking of the polymer chains. The curing step makes the composite production cycle longer comparing to thermoplastic resins. Furthermore, thermoset resins are considered as low-cost sources comparing to thermoplastics.

1.2 Liquid Composite Molding Applications

Liquid composite molding process is a family of composite manufacturing processes in which liquid resin is injected through dry reinforcing preform of the mold until the mold cavity is completely impregnated with the resin system. Afterward the resin curing takes places to obtain the final composite part and as a last step the part is demolded. LCM family has different types according the processing variations, nine common types are listed below:

- Resin Transfer Molding (RTM)
- Vacuum Assisted Resin Transfer Molding (VARTM)
- Seeman's Composites Resin Infusion Molding Process (SCRIMP)
- Injection Compression Molding or Compression RTM
- Reinforced Reaction Injection Molding (RRIM)
- Structural Reaction Injection Molding (SRIM)
- RTM Light Resin Infusion Processes
- Resin Film Infusion.

The selection of each of afore-mentioned methods rely on the designed final part geometry and expected structural properties [1, 4].

1.2.1 Resin Transfer Molding (RTM)

In general, liquid composite molding processes are classified as single or matched sided of mold tooling. Resin Transfer Molding (RTM) is presented as a matched sided mold type of process, as its name implies, for manufacturing parts two or more mold are used according to mold complexity. This method has the advantages of low producing cost and near net shaped parts production. Furthermore, due to the positive pressure of injecting resin the filling is accomplished with higher speed which leads to low cycle time of the process. As it is presented in Figure 1.3 in this method, fiber reinforcement are stacked together to form the fiber preform is placed inside the mold, each side of the mold is compacted to the other side, after enclosing two side of the mold to each other, the resin is injected to the fiber preform, after injection, when the impregnation of the resin is completed it is allowed to cure afterward the part is demolded and removed from mold cavity [5]. It is described that RTM is a two-sided mold type process and this is advantage in terms of the rigidity and stability of the final part due to the high compaction pressure. However, difficulties for flow monitoring during the filling process is a significant concern. Thus, process induced defects during the resin filling can't be detected unless the part is demolded [1, 4].

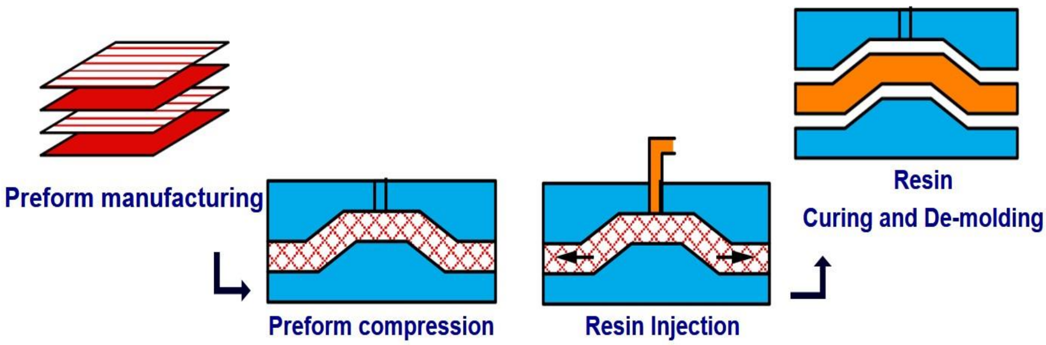

Figure 1.3. Illustration of resin transfer molding (RTM) process

1.2.2 Vacuum Assisted Resin Transfer Molding (VARTM)

Vacuum assisted resin transfer molding is a composite manufacturing method, which is classified as single sided mold filling since the process has one rigid part and the compaction is applied using vacuum chamber. As it is presented in Figure 1.4 the preform is placed on top of the mold and it is covered by vacuum bag and resin inlet and venting tubes are placed to allow resin impregnation and air removal, respectively. The principle of this method for resin impregnation into the preform is pressure difference means that the resin starts to flow through the preform because of the pressure difference between the resin inlet tube and vacuum chamber. The injection pressure for this method is limited with the atmospheric pressure of 1 atm. Thus, the lower pressure gradient across the gates compared to the RTM process makes the filling times longer for the VARTM process. Then, this longer fill times of the preform yields the risk of incomplete filling with the formation of macro voids due to resin viscosity increase with time. Also, this method faces difficulties for filling thick parts. Since the void formation during the filling process of the mold with resin is possible through thickness direction which can't be visualized unless in the top parts near the vacuum bag [1, 6]. However, the single molding surface makes the process more cost-effective compared to the RTM process.

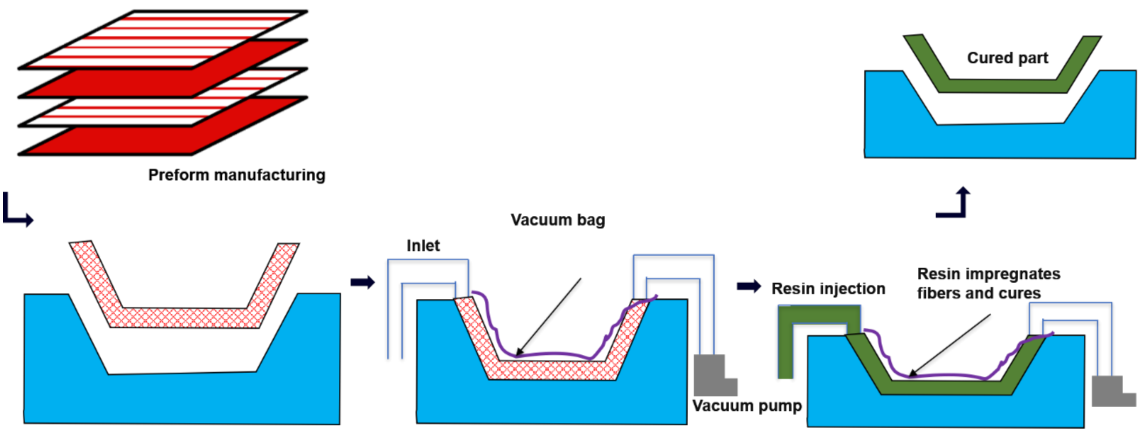

Figure 1.4. Illustration of vacuum assisted resin transfer molding (VARTM) process

1.2.3 Seeman Corporation Resin Infusion Molding Process (SCRIMP)

In order to overcome long filling time of VARTM process to yield a high composite production rate the Seeman Corporation resin infusion molding process (SCRIMP) is developed. This method has the same principle as VARTM and is from the resin infusion types of process. It is presented in Figure 1.5 that the only difference is the existence of a single or group of highly permeable layers. These layers are called as distribution media (DM)layers and added on the top of the preform. The addition of this DM on the top layer of the preform promotes the resin flow to impregnate in to the preform due to the low resistance for resin flow of the DM. Additionally, it enhances the flow distribution through thickness direction. The clamping pressure for compaction in SCRIMP is lower than RTM [1, 7, 8].

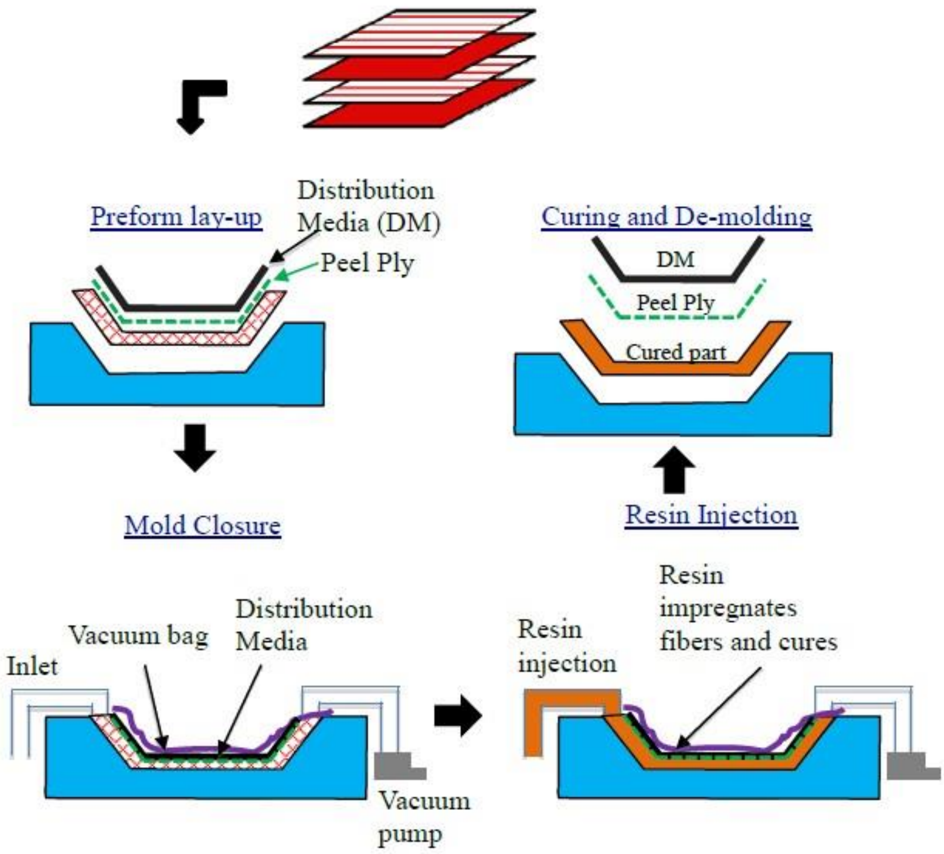

Figure 1.5. Illustration of Seeman Corporation resin infusion molding process (SCRIMP)

1.3 Resin Rheology

Every fluid substance represents a specific arrangement of molecules. When the fluid starts to flow, it means that the arrangement of molecules starts to change, and the resistance to it is called as viscosity. Resin viscosity is contributed to pressure and velocity values since those terms are calculated using the equation of motion. On the other hand, the viscosity itself is a function of temperature, pressure, shear rate and the degree of the cure. For isothermal processes, the temperature kept constant as time pass while for non-isothermal processes temperature varies with time. Thus, for isothermal processes the chemical reactions inside the resin, leads to viscosity increase, means that pressure, velocity and filled parts profile change with time. The gel time of the resin is another parameter, relates to viscosity. Gel time is defined as a time that resin become highly viscose in a way that, it could not proceed anymore. Higher values of viscosity lead to gelation of the resin happens sooner. [1, 9, 10].

1.4 Race Tracking

During the filling process some parts of the mold remains unfilled while the resin reached the outlet gate and the filling is accomplished unsuccessfully. Generally, the small gaps between the preform fibers are defined as race tracking possibilities. Since, defined gaps lead to higher permeability values in the occurring places, the resin impregnate to these areas is faster than any other places in the mold. The reason for variation in flow pattern is defined as resistance for flow in different parts of the mold means that the low resistance to the flow in gaps lead to faster impregnation of the mold to the resin, in other words the race of flow in these areas happen. To illustrate the effect of race-tracking occurrence on the flow patterns, resin flow in the rectangular mold cavity is modeled with defined inlet and outlet locations via LIMS [11] with different race-tracking possibilities. As it is shown in Figure 1.6 the flow distribution for the same gate locations is different and the different impregnation velocity in different parts of the mold leads to un predictable flow patterns. These unusual filling profiles lead to uninform distribution of resin in the mold. This phenomenon, race tracking, happens in a way that the resin flow reaches the outlet gates while some parts of the fiber preform remained unfilled. As a results, race tracking phenomena lead to void formation during filling process [1,5 , 11, 12].

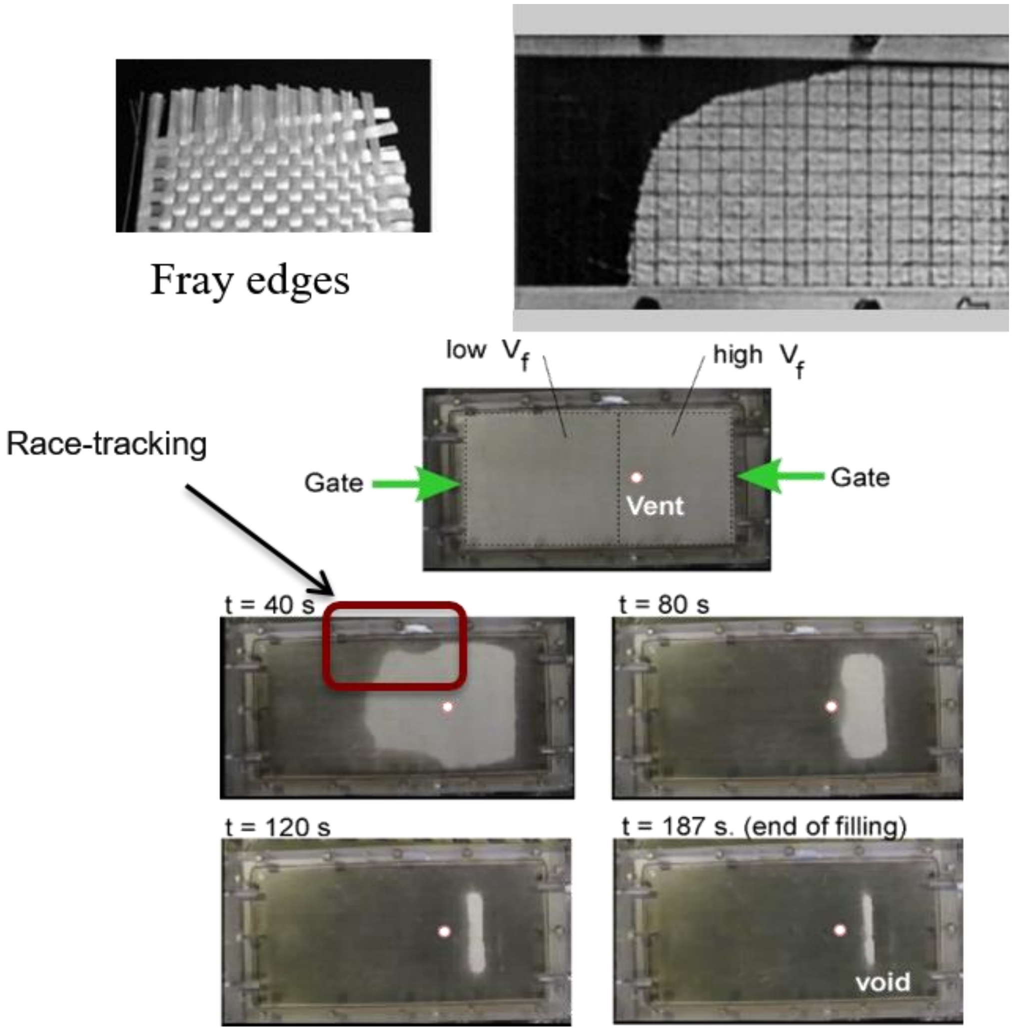

Figure 1.6. Flow distribution in the existence of race tracking

1.5 Liquid Composite Molding Process Modeling

One of the important factors to determine the governing equation of the problem is considered as flow scale. Thus, the resin flow through fiber preform may studied in two scales, Macroscopic flow, and microscopic flow. The flow between the fiber bundles is in the macroscopic scale, however the flow within the fibers is in the microscopic scale and the interaction between these two scales of flow lead to void formation. The basic mathematical model for flow through porous media is based on continuity equation, which reflects the idea that mass is conserved. If resin assumed as a Newtonian liquid and fiber preform as an incompressible porous domain the macro void formation can be easily predicted by Darcy law and mass continuity equation, Darcy's law holds only for a Newtonian fluid over a certain range of flow rates with Re=25 as a upper limit for the validity of the equation, however for micro void prediction, terms like degree of saturation and capillary pressure is added to both equations, respectively [14]. As a result, mathematical modeling of the resin flow in LCM process is described reasonably well as flow through porous media using Darcy's Law coupled with the continuity equation.

$$\langle \mathbf{v} \rangle = -\frac{\mathbf{k}}{\mu}.\nabla P \tag{1.1}$$

$$\nabla \cdot \langle \mathbf{v} \rangle = 0 \tag{1.2}$$

$$\nabla \cdot \left(-\frac{\mathbf{k}}{\mu}.\nabla P\right) = 0 \tag{1.3}$$

where $\langle \mathbf{v} \rangle$ is the volume average velocity, **k** is the permeability tensor, μ is the resin viscosity and ∇P is the pressure gradient of the resin system, **k** as shown (in Cartesian coordinates) in Equation (1.4), represents how easily resin can flow in the corresponding flow direction.

$$\mathbf{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \tag{1.4}$$

Darcy's Law, which relates the resin pressure gradient with the resin velocity, requires two material properties: permeability tensor of the preform and the resin viscosity. Permeability tensor is a preform property and indicates the ease of flow through the preform. There are two methods to measure the permeability: saturated permeability measurement and unsaturated permeability measurement [15]. In the first method, liquid is passed through the pre-form which is fully saturated by the liquid. Flow rate is maintained constant, and the pressure difference is measured between two different points (usually the liquid inlet and outlet). The pressure gradient is obtained by dividing the pressure difference by the distance between the pressure measuring points. Permeability can then be obtained. The permeability value obtained in this way is called the saturated permeability. The second method utilizes an unsaturated flow where the preform is progressively impregnated with time. The inlet pressure is fixed at a constant value, and the resin flow-front advancement is recorded with time. From Darcy's law, we can obtain an analytical solution for 1D flow-front position as a function of time, given the constant permeability and liquid viscosity. The slope of the curve of square of flow front position with time gives a value for the permeability in the corresponding flow direction. By introducing radial flow with flow monitoring at the top and bottom surfaces of the preform permeability can be experimentally estimated as a tensor using proper arrangements, three-dimensional permeability can be measured. The permeability measured in the Transient flow condition is called the unsaturated permeability [16]. generally, for the LCM models the permeability value is assigned as a bulk property, with the assumption of uniformity of the fibrous domain. This generates simple, deterministic model but as any material property variations, geometrical variations and lay-up of the assembly generate variations in permeability values, there will be some differences between real and predicted flow patterns.

1.6 Numerical Simulation of LCM

Various numerical methods have been implemented for resin flow simulation in LCM processes. The basic idea for numerical simulation is to obtain the variable values from the set of the distributed points as nodes in the domain. A set of algebraic equations are needed to relate the variable value at a local point to the neighboring points. these set of equations can be achieved using different adaptations as Finite Difference Method (FDM), Finite Element Method (FEM), or control volume/finite element (CV/FEM) [13,14, 16, 17, 18, 19, 20, 21]. Using FDM, the derivatives in governing equations of the problem are replaced with difference equations, as a result solution can be specified to discrete mesh points in the problem domain. The basic idea for FEM is defined as dividing the problem domain into small subdomains, and the local solutions are found these small sub domains are considered as preliminaries to find the global solution. Global solution is found by combining the local solutions together [23]. The principle for CV/FEM is proposed in the following. In order to find variables of the given problem first node points are introduced to the solution domain using various types of domain discretization methods. One may discretize the given problem domain using any of three main approaches as: 1) gridding, 2) meshing, 3) clouding. Using the gridding of the domain, structured discretization is applied to the main, means that assuming a 2-dimensional domain the location of each node is specified by a certain column and row. This type of discretization is problematic for complex domain geometries. In other words, discretization of complex geometries with a structured grid implementation may not be possible due to the possible arbitrary corners or shapes of the domain thus gridding isn't a flexible type of discretization. Meshing as another type of discretization is able to be applied in unstructured type. unstructured mesh can be easily applied to complex geometries since it has irregular connectivity between points. the last type of discretization can be mentioned as mesh less discretization, means that in this method neither meshing nor gridding is used for discretization, but the neighboring nodes which are in the defined length distance for the central node, are used for approximation of algebraic equations. The mold filling in LCM is moving boundary problem since the flow front position is changing continuously as time pass. The moving boundary approach in numerical methods is computationally difficult and time consuming specially for the complex domain with inserts and multi gates. However, the fix grid approach doesn't face those mentioned problem since the newly achieved boundary for flow front in each time step isn't remeshed. But to have accurate results for fixed grid approach the moving boundary nature of the problem should be applied with other terms. FDM is applied for two dimensional problems and it is further enhanced with boundary fitted coordinate finite difference method for complex geometries. Also, BEM solved the remeshing problem for complex domains, but the mass conservation isn't satisfied locally. By using this method. Coulter et al. used BEM to solve two dimensional Darcy law for quasi-steady flow in anisotropic fibrous preforms at each time step and a code TGIMPG was developed and tested experimentally for various cases with arbitrary shaped performs [22, 23]. The standard FEM is mentioned as another method with the same problem of local mass conservation as FDM [26]. Chan et al. developed computer code based on finite element to simulate mold filling in a 2-dimensional domain. finite element with quadrilateral elements is used to model the RTM of "thin" composite parts using a 2-dimensional approximation, the work is applied to anisotropic perform along with viscosity variation during filling [27]. Nonconforming finite element method is another method based on fix grid approach, the same as FE/CV approach the conservation of flow rate for inter-element boundaries ensured by this method. Trochu et al. used nonconforming finite element method with triangular elements implementation, the fix grid approach is adopted and the fill factor is assigned to each element instead of nodes [19]. As a result, FE/CV method is the most preferred approach since it is based on fix grid approach. For CV/FEM method, the discretization is adopted in meshing format. CV/FEM method overcome the problem of CV/FDM method using unconstructed mesh adaptation, control volumes are adopted around the node point in the mesh. Also, fluxes across the control volume faces approximated using finite element method. The flow front is tracked by partially filled control volumes. Burschke et al. used a FE/CV approach to investigate flow pattern in non-isotropic porous medium with varying thickness, during the filling process, the domain is filled with multi gate adoption [26]. A hybrid numerical method is applied by two dimensional triangular elements are implemented to mold geometry and time derivatives applied using FD and a control volume approach is used for numerical formulation and is applied for 2-dimensional and 3-dimensional parts [28]. Resin flow through fiber preform can be simulated using any of the aforementioned techniques.

1.7 Optimization of Liquid CompositeMolding Process

In order to ensure final part quality in the minimum processing time the optimization of the process plays an important role. In other words, the main goal for filling stage optimization is defined as the minimum time for the resin to fill the part completely or within the given tolerance [19], [29], [30]. In this regard, one of the main approaches is defined as gate location optimization. Means that different inlet and outlet locations lead to different filling profiles with specific void formation associated to each of them. As mentioned previously, the other factor that changes the flow profile defined as race tracking phenomena. Both factors are essential to be consider in optimization problem. Since the manufacturing polymer composites is a design problem, optimization of the problem is significant to make the fabrication achievable for any type of industry. the optimization is applied to any problem by using a selected optimization algorithm. Among the various types of optimization algorithms, one must understand the physics of problem totally to choose the proper algorithm. Generally, optimization problems consist of an objective function and design variable or constraint. Objective function is defined as the objective of the problem to be minimized or maximized and design variable is defined as the parameter that influence the objective function. Meaning that the objective function is minimized or maximized according to design variables contributing on the problem. As a result, optimization problem can be studied using different point of views. In general, optimization problems can be categorized from couple of points of view. If the optimization problem is assumed as constraint problem, it means that the problem variables must satisfy a single or group of constraints, in contrast in unconstrained problems, variables are free to change without satisfying any constraint. As another point of view, optimization problem can be classified in to discrete and continues forms, it means that design variables are in stated form. The other classification of optimization is related to dependence of the objective function to time. The problem is dynamic optimization if the optimum answer changes with time otherwise it is a static optimization problem. Various types of optimization algorithms exist to solve optimization problems. Generally, optimization algorithms are divided to three main group of: 1) deterministic algorithms, 2) stochastic algorithms and 3) hybrid algorithms. Deterministic algorithms are the types that the optimal solution for the same input parameters don't change in each run, means that if one runs the problem several times the answer wouldn't vary. The problem for this type of algorithm is defined as getting trapped in local optima. In contrast stochastic algorithms are based on randomness, and they don't require intensive computation like deterministic algorithms. Furthermore, these algorithms give different answers in each run, but the answer is near global or global. The last types of algorithms are combination of multi algorithms to solve the same problem in a way that the weak point of each of the algorithms in any part of the problem is neglected by subsisting another algorithm with higher potential to solve that specific part of the problem. Many research have been conducted in molding and optimization of gate and vent locations in LCM processes, Mathur et al. optimize the gate and vent locations without considering the effect of all possible race tracking [31]. Kim et al. used GA for optimization of gate locations with sequential injection adaptation without consideration of race tracking [32]. Jianga et al. used GA to optimize gate and vent locations with adaptation of mesh distance concept without the presence of race tracking [33]. Gokce et al. used integration of branch and bound search and map-based exhaustive search adaptation for simultaneous gate and vent optimization in presence of race tracking [34]. Hsiao et al. used GA to optimize flow distribution network with experimental validation [34]. Ye et al. proposed simulation-based black box optimization method using heuristic algorithms for RTM processes and the optimization problem is solved for one gate with multiple vents which is presented as an open case to be extended for multi gates and other process parameter variables [35]. Wang et al. used iterative search to find optimal Centroidal Voronoi Diagram (CVD) of mold surface, the optimal CVD include the optimal gate location, optimal gate location is adopted to satisfy the only objective of the optimization as minimum fill time. Race-tracking effect and accurate viscosity adaptation are not considered in RTM simulation and optimization [36]. Hsiao et al. used GA to optimize flow distribution network with experimental validation, for a predefined gate and vent location without race-tracking adaptation in simulation and optimization stage [37]. Sas et al. used discrete optimization for distribution media design of the predefined gate and vent location, the optimum design selected in a way that all race tracking possibilities are taken in to account [38].

1.8 Objective and Dissertation Outline

The objective of this thesis study is to develop a methodology to optimize filling stage of Liquid Composite Molding process. Two factors considered as the objective of optimization problem: i) minimum void content ii) minimum fill time. In order to achieve this the optimization study is carried out in two stages. The output of the first stage of optimization is defined as inlet and outlet (namely gates) locations with the input of the geometry of the part, location and strength of flow disturbances, the inlet and outlet pressure or flow rate boundary condition at the gates. On the other hand, the second stage of optimization is carried on by distribution media layout optimization with the outputs of first stage as the inputs in the second stage of optimization. Using two stages of optimization instead of each of them alone, reduce the complexity of optimization problem. Furthermore, this study investigates the effect of viscosity parameter and race tracking phenomena in the simulation and each stage of the optimization.

In this thesis an introduction to composite materials and Liquid composite molding is presented in Chapter 1. Afterward a methodology to optimize the filling stage of LCM process using Genetic Algorithm and Tree search Algorithm for gate and distribution media optimization is described respectively in Chapter 2.

In Chapter 3 the results of each optimization stage are presented. Also, example mold geometries are presented the optimum gate locations and distribution media design is achieved. Furthermore, the effect of race tracking phenomena and viscosity is discussed in each stage.

In Chapter 4 as the last chapter includes the conclusions and contributions with suggestions for future work.

2 OPTIMIZATION OF GATE LOCATIONS AND DISTRIBUTION MEDIA LAY-OUT

Each method in liquid composite molding processes has some advantages and disadvantages, one of the main disadvantages of RTM type processes is defined as sensitivity of them to gate locations, means that improper selection of gate location may lead to incomplete filling of the preform with resin system. The empty spaces in fiber preform are resin starved parts in composites and lead to the poor quality of final part. Thus, gate and vent location design are significant in order to overcome this issue, in other words the inlet and outlet locations should selected in a way that, the given gate locations fill the dry preform with minimum void formation in a minimum filling time. On the other hand, for other processes in LCM family like VARTM or SCRIMP, further enhancement of resin impregnation could be achieved using a highly permeable layout (distribution media). The distribution media is added to the top or bottom of the preform. Providing this resin impregnation into the dry fiber preform is accomplished in less time. Since the DM layout can be added to any part of the mold, design of DM layout proposed as an effective way to overcome flow disturbances [5, 7, 38, 39].

2.1 Methodology and Implementation

Optimization of gate locations and DM layout design is adopted in two separate optimization stages. In the first stage, Genetic algorithm is adopted for gates optimization. In order to optimize gate locations, simulation of the process should be carried out in the first step. The data acquitted from the simulation stage is used for optimization stage. in the second stage of optimization an optimum design for DM layout is proposed. In this stage, the optimum gate location from the first stage is implemented to the DM design optimization as the input data. Tree search algorithm as a discrete optimization is adopted to obtain optimum arrangement of DM layouts. For both optimization algorithms the evaluation of objective function is carried out by Liquid Injection Molding Simulation

(LIMS) a software package developed at the University of Delaware [40]. LIMS uses finite element/control volume approach to simulate the resin flow through porous media. As stated in introduction section Darcy's Law and mass and energy conservation are defined as governing equation for simulation of resin through porous media. The problem is simplified by applying optimization in two separated optimization algorithms. Using this adaptation make the problem possible to handle in terms of complexity comparing to the case of using each of algorithms alone to find the solution. The following sections described the details of each optimization stage [41].

2.2 Adaptation of Heuristic Optimization for Gate Optimization

Heuristic optimization algorithms are proposed as appropriate optimization techniques for real world problems. Generally, these algorithms are mentioned as appropriate solutions for the problems that classical algorithms fail to find answer, or the computational time is too long. The main principle of all optimization algorithms is to find the optimum value for independent variables for which the objective function reaches to its maximum or minimum value. Among the various search techniques for gate locations, gradient-based methods tend to trapped in local minima and the results are highly rely on initial guesses, instead stochastic search techniques like genetic algorithm has the advantage of proposing near global solutions specially for large domains with higher possibility of being trapped in local optimums [42].

2.2.1 Genetic Algorithm

Genetic algorithm is classified as stochastic search optimization methods. It is defined as heuristic search techniques. These algorithms also belong to a class of methods known as evolutionary methods or nature-inspired methods since it is based on Darwin's theory of evolution by natural selection or in other words survival of fittest. The terms contributed to GA implementation are defined as: genes, chromosomes, population and generation[43].

The value for an independent design variable is presented as gene or individual components. The most used encoding for gene representations are: Binary representation, Integer representation, Real-valued representation, Permutations representation. Each type of mentioned encodings is used to represent the values of each gene. chromosomes are presented as a set of genes. Since each gene represent the one of the design variables of the problem, a single chromosome as a set of genes contain the value for all design variable contributed to the problem. A set of chromosomes are presented as population, since each chromosome is associate to the specific design of independent variables in the problem. population as a set of chromosomes are defined as a set of possible designs. Each generation has the population with the same size, in other words iteration of a complete genetic algorithm lead to generation formation.

The main steps for genetic algorithm adaptation are presented as:

1. Generation of initial population
2. Parent selection
3. Recombination
4. Mutation

The basic idea of the approach is to start with a set of designs, randomly generated using the allowable values for each design variable. as mentioned before each chromosome defined as a specific design of independent variables. Chromosomes are created randomly and a fitness value from evaluating each chromosome with fitness function is assigned to each set of design. Fitness function is defined as function including objectives of the problem. Meaning that for the given design fitness function evaluation gives the answer of how much the objectives of the problem satisfied. The next steps in GA algorithm are presented as reproduction procedure. In this process best fitted chromosomes are selected with various schemes to move from current generation to the next generation, Selection schemes for reproduction process are divided to two main groups of Fitness-Proportionate selection (FPS) or Ordinal Based selection (OBS).

As it is presented in equation (2.1) the probability (p) that an individual f_i is selected for mating pool is depends on absolute fitness of individual compared to absolute fitness of rest of the population

$$p = \frac{f_i}{\sum_{j=1}^{l} f_j} \quad (2.1)$$

Ordinal based selection attempt to remove problems of FPS by basing selection probabilities on relative rather than absolute fitness Population sorted by fitness and selection probabilities based on rank, not to their actual fitness. [44] The basic idea for reproduction process is defined as chromosomes with higher fitness values are the ones with higher probability to be selected for the next generation. The reproduction procedure is continued until the stopping criteria is satisfied or iteration reached to its final limit. Reproduction procedure consists of two main groups of crossover and mutation. After the chromosomes are selected according to the appropriate selection scheme associated with the problem, crossover is applied to the population to introduce variations into current population. Crossover is conducted to two set of design variables (chromosomes), to mix two designs. This combination can be applied in different methods, the most common methods to perform crossover is defined as one-point crossover and two-point crossover, the chromosome is cut according to the number of cut points, cutting is applied to the random or predefined location of the chromosome. For example, in one-point cut crossover, both chromosomes are cut from the specific point, and the resulting 4 halves are combined or exchanged to produce a new pair of chromosomes(designs). Mutation is defined as another reproduction process, the location for mutation is selected randomly. The genes of selected locations in the chromosomes are replaced with a new design variable. The number of chromosomes selected for mutation is based on heuristics. In each generation the size of reproduction is the same as the size of the population. The amount of crossover and mutation is defined by user, in a way that the performance of the algorithm increases in each generation.

higher values of fitness function are defined as the best fitted designs. As a result, for each generation in GA a pair of best fitted chromosomes are selected as parents for the current generation. Crossover and mutation are applied for parents to produce offspring. Each offspring's fitness from newly produced generation is evaluated. The fittest chromosomes are survived to next generation and the rest are eliminated. Using this approach eliminate extinctions of deigns with minimum or maximum value for objective function according to the problem, in each generation. The loop for reproduction continued until a user defined satisfying values for objective functions are accomplished.

2.2.2 Genetic Algorithm Adaptation to Gate Optimization

Details for GA adaptation is shown in Figure 2.1 dimensions of each coordinate for the all nodes of the mold domain is the primary concern to make chromosomes thus, assuming two inlets and two outlets for a three dimension mold geometry result in a chromosome with 12 genes. A random population of chromosomes are created as an initial population. Each chromosome is evaluated for all race tracking possibilities defined previously in the problem, means that if the four edge of simple rectangular domain is assumed as possible places for flow disturbances (race tracking). 2^4=16 is total number of race tracking configurations that may happen during the mold filling and the objective function is evaluated for all mentioned configurations. The case with maximum void content and fill time is chosen as the worst case for the given gate locations among all 16 possible scenarios. The fitness function (f) for the problem is defined as equation (2.2)

$$f = w_t \frac{t_{fill}}{t_{gel}} + w_v \frac{v_c}{100} \qquad (2.2)$$

where w_t are user defined weight coefficient for void content and fill time with t_{fill} and t_{gel} gel time for the resin system; and w_v is user defined weight coefficient for void content with v_c is the void content as percentage.and the objective is to minimize the f value. The fitness value for the worst cases of all chromosomes in the population is evaluated. Parents for new generation are selected from the initial population of chromosomes. crossover and mutation are applied to the parents in a way that produced offspring have gates and vents in opposite side of the mold, this constraint eliminate the calculation of obvious incomplete filling. population production continued until the new generated population size reaches the equal number as previous ones. Chromosomes of each population are sorted according to their fitness, the ones with lower fitness are eliminated, among the survived ones, chromosomes with higher fitness have the higher probability to be selected as a parent. New population generation is continued until there exist a gate configuration in population with allowable limits as void content and fill time. Means that the objective function of worst case for the proposed gate locations among the all possible race tracking must be within the allowable limit. Genetic algorithm is classified as probabilistic algorithms, which is subset of larger branch of computation known as evolutionary computation, it is search based algorithm based on the concepts of natural selection and genetics which imitates Darwinian evaluation, unlike the gradient based techniques the algorithm is capable to find near global solution It starts from generation of initial population, population is a set of chromosomes which consist of gens. Chromosomes evaluated according to their fitness, and are sorted, best fitted ones are survived for the next generation and rest of them are eliminated, first generation starts from selecting parents from the survived group of chromosomes, the next step is mating of the parents to produce offspring so crossover and mutation is done between the parents and the produced offspring are evaluated according to their fitness, if the results satisfy the optimization condition, algorithm stops, other way it continues to generate new parents and offspring until the condition is satisfied. Figure 2.1 represent the steps of genetic algorithm adopted in this study. also, LIMS software is used together with this algorithm to obtain the results. As a first step genes of chromosomes are node dimensions exist in the geometry of the problem, so each chromosome contains inlet or outlet node information and a set of randomly selected chromosomes make initial population. Whiten this algorithm, results for each set of inlets and outlets are evaluated with LIMS, for each case results of all possible race tracking are calculated and the case with bigger amount of void is selected as a worst case , Chromosomes are evaluated according to their fitness, the ones with inlets and outlets that lead to less formation of voids and complete filling of the mold before the gel time of resin are the fittest.. The population of next generation is selected from the best fitted chromosomes and rest of them are eliminated, mating is done between genes of chromosomes with higher probability to select and crossover and mutation transformation is done ,recombination continued until population of new generation reaches to N, the fitness of each generation increases because of being made by fitter parents and generation production continued until optimum results are achieved.

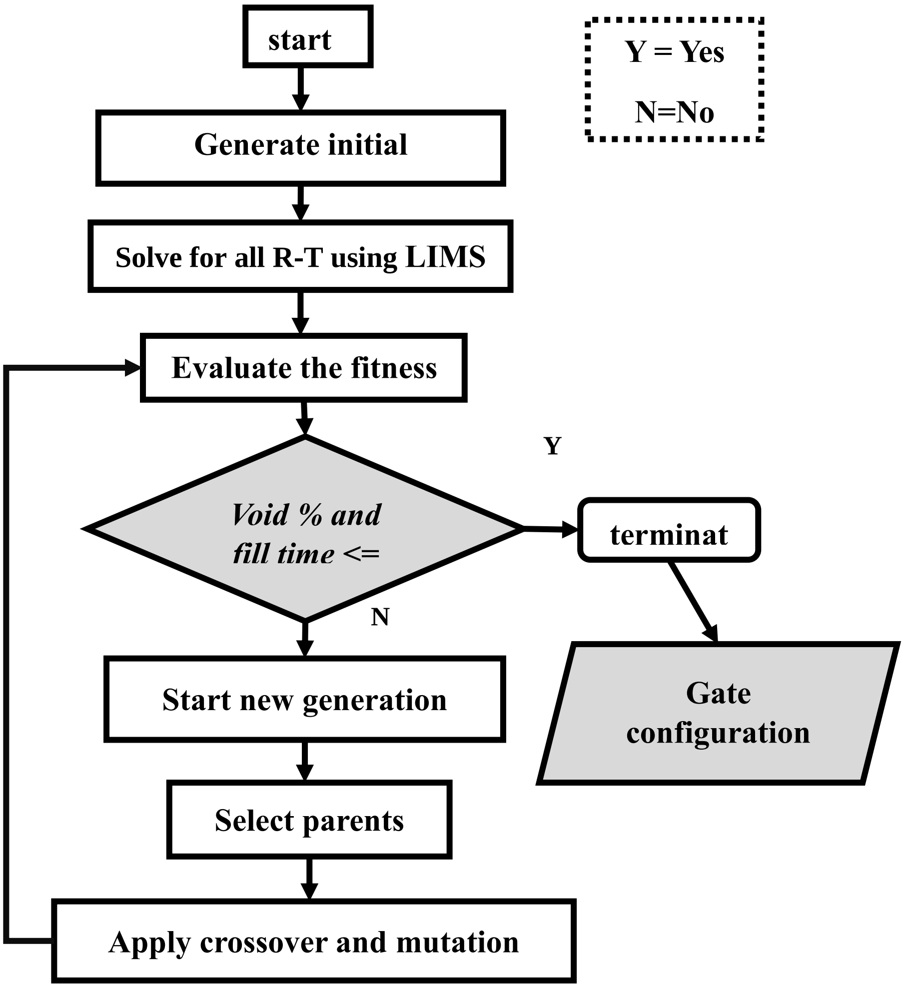

Figure 2.1. Genetic algorithm flowchart for gate location optimization

2.3 Discrete Optimization for Distribution Media Layout Design

For the given part geometry optimum gate locations are obtained using the first stage of optimization. The second stage of optimization is adopted to find the optimum arrangement of distribution media layout in the mold geometry. In the past, researchers have published DM optimization using GA and discrete optimization techniques. The prior study didn't mention disturbances due to race tracking during simulation and optimization stage. The former study also used race tracking as a design variable but still viscosity variation during mold filling stays as a significant concern for the optimization problem. Optimization of DM arrangement proposed as discrete optimization since the variables and potential solutions are finite. From this family of optimization type a deterministic algorithm as tree search algorithm is chosen for DM placement in the mold [45].

2.3.1 Tree Search Algorithm

Tree search algorithms according to the search methodology are classified to two main group of Blind search algorithms and Best-first search algorithms[40]. As mentioned earlier the empty locations of the mold which remained unfilled are the results obtained from first stage, means that even for large scope geometries DM placement possibilities are known and still small enough to handle with discrete techniques instead of heuristic ones thus blind search class of algorithm is chosen. As mentioned in [38]. breadth-first and depth-first search are two main search techniques for blind-search algorithms. the depth search is adopted to tree search algorithm since not all the conditions in the same step are calculated and but a single path for one of the conditions is continued until the results are obtained. DM implementation is applied to the mold in a way that optimum number of DM layouts in optimum size cover the obtained unfilled domain during the filling, In other words, for the obtained flow distribution of given gates in the first stage optimization, the empty regions of resin are determined thus the mold region is divided to optimum number of sub regions. The optimum number of sub regions for DM defined as minimum number of regions that if a DM layout is placed in a subregion corresponding to the unfilled domains, the domain is covered completely without covering unnecessary parts. After the assumption is made for the number of regions the next defined as DM placement to each sub region one by one until objective functions are minimized to allowable limits. The obtained DM configuration is examined for another race tracking possibly. In other words, the DM design is finalized if the objective function for all race tracking possibilities of that design is within the allowable limits.

If the objective functions. If the constraints for objective function aren't satisfied first the algorithm continued to add DM layout to multi regions of the mold and then the number of regions is increased until the objective functions are satisfied. Details for discrete optimization is presented in Figure 2.2 gate locations with race tracking configuration of worst case are pre identified to the problem from GA adaptation. The next step is proposed as region division to optimum number of sub regions by using k-means++ algorithm of MATLAB [45]. The mold region is divided to 2xk region, k starts from one, and the DM layout is placed in each of the regions and the objective function is determined for all possible race tracking scenarios of each DM implementation. As mentioned before the allowable limits for objective function is defined by user. the DM included region that satisfies the limits for objective function is assumed as winner arrangement for the presented step of calculation. The next step is defined as checking the obtained DM included mold for other race tracking possibilities, if the objective function for all race tracking scenarios is in the allowable limits the problem stops and DM designed is completed otherwise the algorithm started other loop of total 2xL loops to add DM, if the condition for objective function aren't satisfied for the last loop either, the number of regions is increased to k+1. Thus, total number of regions and loops are 2x(k+1), 2x(L+1) respectively, again in each loop distribution media is placed on each region one by one and the best result of each loop is chosen to be checked for other race tracking scenarios. The worst case is chosen among the possible scenarios to be treated by DM implementation. elemental data are updated at the end of each loop and the next steps are proceed the same as the first run of the algorithm [46].

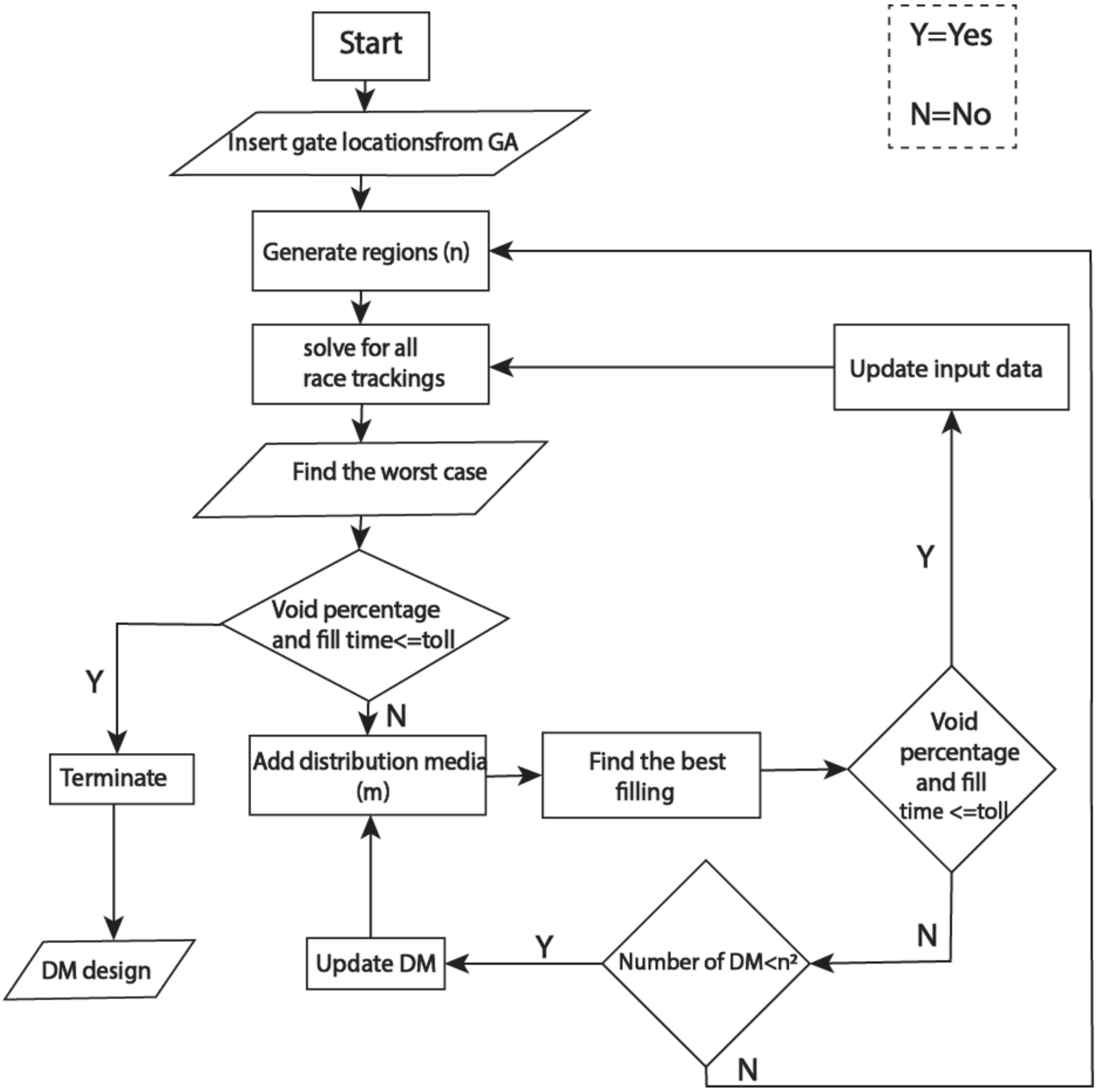

Figure 2.2. Discrete optimization flow chart for distribution media (DM) layout design

3 RESULTS AND DISCUSSION

In this chapter, the obtained results from the presented numerical methods in pervious chapter are presented and discussed. It is shown in pervious chapter that the filling process optimization of LCM process is adopted in two stages. Accordingly, results are presented in two parts, the first part is related to the first stage of optimization, the optimum locations for the gates is achieved in the first part. For the second part of the results, the optimum gate arrangement achieved from first stage is used for distribution media (DM) design. In order to investigate the effect of viscosity and race tracking in filling stage of RTM type of processes, results for different race tracking possibilities in two types of viscosity adaptation are compared. Table 1 represented the material properties used in both simulation and optimization stage.

Table 3.1. Material properties for model simulation

Parameter	**Numerical Value**
Fiber volume fraction, v_f	50 %
Permeability of fiber preform	$K_{xx} = 1 \times 10^{-10}$ (m^2) $K_{yy} = 2 \times 10^{-10}$ (m^2)
Permeability of race-tracking channel	$K_{RT} = K_{xx} \times 1000$ (m^2)
Fiber volume fraction of DM	20 %
Permeability of DM	$K_{DM} = 3.5 \times 10^{-9}$ (m^2)
Viscosity of resin (function of time, t)	$0.0256 + 4 \times 10^{-6} \times t$ (Pa · s)

As it is presented in Table 1, the race tracking is modeled as a material property which is related to the permeability of the fiber perform. Since the existence of race tracking enhances the resin flow distribution and generates uneven and unexpected flow patterns, it can be modeled by the assignment of race tracking permeability of the fiber in locations which are prone to race tracking formations. Additionally, the implementation of distribution media is adapted to the model via the definition of permeability parameter for distribution media, KDM. Viscosity is the other prominent parameter in LCM modeling which alters the process success. Thus, the process model reliability should be investigated with more realistic model for the viscosity. In this content, the variation of resin viscosity with time is adapted using one of the preferable epoxy resin system, Hexflow® RTM6, data sheet [47]. As it is stated in the data sheet, resin is considered as premixed epoxy system for service temperatures from -60 °C up to 120 °C. The viscosity changes with time at 120°C processing temperature is fitted with linear equation as it is presented in Table 3.1. The gel time is a critical limit where the resin flow nearly ceased is a critical time limit for the LCM modeling. For the resin system at 120 °C the gel time is considered as 240 (mins).

3.1 Race Tracking and Viscosity Effect

For the given simple rectangular mold presented in Figure 3.1. 4 edges of the rectangle are considered as probable parts of the mold for the occurrence of race tracking phenomena and are shown with red lines. Total possible scenarios or different race tracking arrangements are 2^4=16. It is presented in Figure 3.1. for the user defined line injection and line outlet. Two of the race tracking scenarios are selected and flow distribution with time is shown. It is shown that flow distribution with time is different for each race tracking scenario. The resin impregnation and the amount of void content varies in each scenario. Furthermore, the fill time is also different in each scenario. As a result, for the given inlet and outlet the void content and fill time is different for each race tracking scenario. Also, the effect of viscosity is investigated in Figure 3.1. the flow distribution with time is investigated for two types of viscosity adaptation. as a first type, viscosity for the isothermal filling process considered as constant parameter μ=0.0259 and in the second type viscosity is adapted as changing variable with time as μ=0.0259+0.00004xt. Resin type and its viscosity is chosen from RTM 6 datasheet and presented in Table 3.1 previously. It is shown that the fill time of the resin varies in each type of viscosity adaptation. Also, the difference in fill time for constant and variable viscosity adaptation varies for different race tracking scenarios. In the following sections the effect of viscosity and race tracking is shown in optimum gate adaptations.

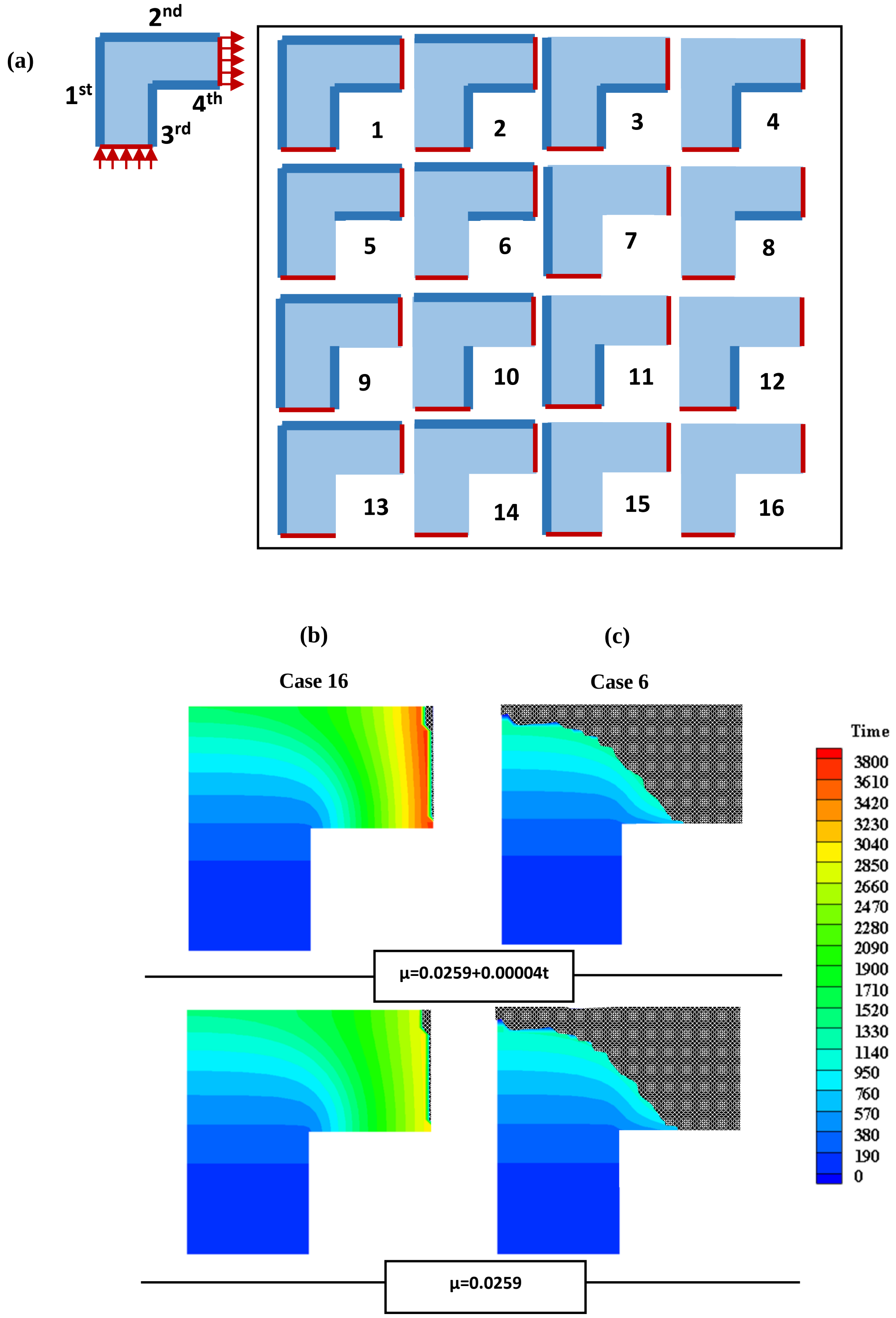

Figure 3.1. Flow distribution for different race tracking scenarios. (a) different race tracking scenario for line inlet and outlet, (b) flow distribution for race tracking case 16 (top: variable viscosity, bottom: constant viscosity), (c) flow distribution for race tracking case 6 (top: variable viscosity, bottom: constant viscosity).

3.2 Single Gate Optimization

3.2.1 Race Tracking Effect in 2D Rectangular Mold Geometry with Optimum Gate Adaptation

For the given mold geometry in Figure 3.2.a, the optimum single inlet and outlet locations is presented. The optimum gate locations are found assuming 4 edges of the rectangle mold as probable locations for race tracking. The race tracking scenario with maximum void content and maximum fill time is scenario 13 with 14.6% as void content and 72.08 seconds as the fill time. Although, the 2% of allowable void content isn't satisfied with the optimum gate locations found by Genetic Algorithm but it is considered as the best possible answer. It is shown in Figure 3.2.b that the flow distribution with time varies significantly even for the cases with optimum gate locations. The void content changes from a scenario with lower limit of void content of 0.25% to the case with the highest void content of 14.6%.

In order to show the differences flow distribution in Case 13 and case 16 are compared in Figure 3.3 It is shown that the filling pattern is completely changed and alter the time that the resin reaches to outlet gate. As another impact of filling pattern variation, the fill factor of both cases are compared in Figure 3.4. It is shown that different parts of the mold remained unfilled for each scenario. Also, the total number of empty nodes at the end of fill time varies for each case. Figure 3.4.a presented the fill factor of each node after the mold filling is accomplished for 13th scenario while the empty percentage of the mold is 14.3% and in Figure 3.4 b the fill factor distribution for 16th scenario is presented while the void content is 2.7%. As a result, the existence of race tracking lead to different filling pattern and void content for the same injection scenarios.

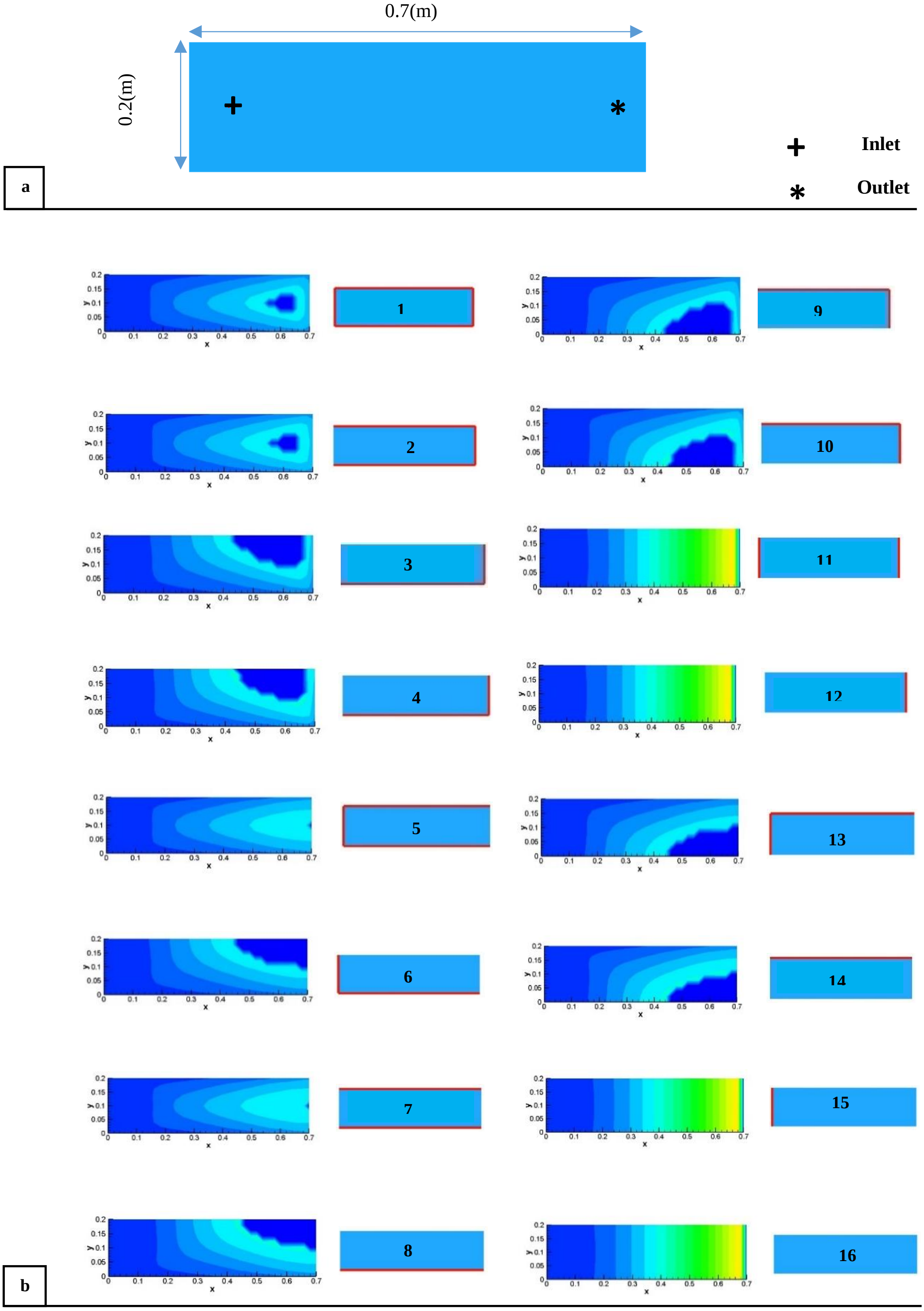

Figure 3.2. (a). Inlet and outlet locations in the given mold (b)flow distribution for different race tracking scenarios

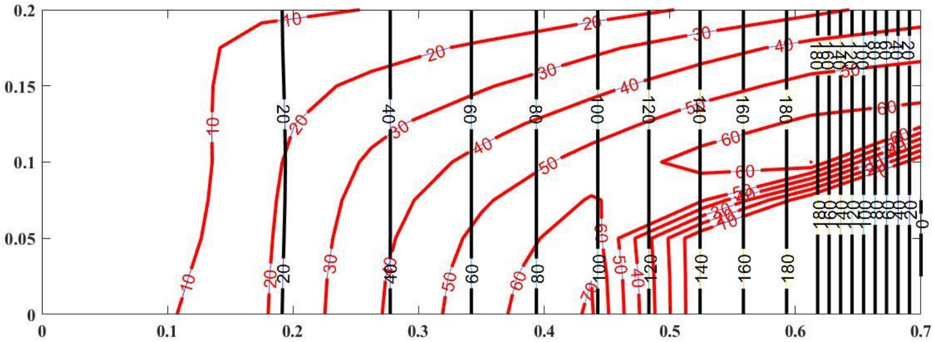

Figure 3.3. Comparison of case 13 (red line) and case 16 (black line) filling pattern

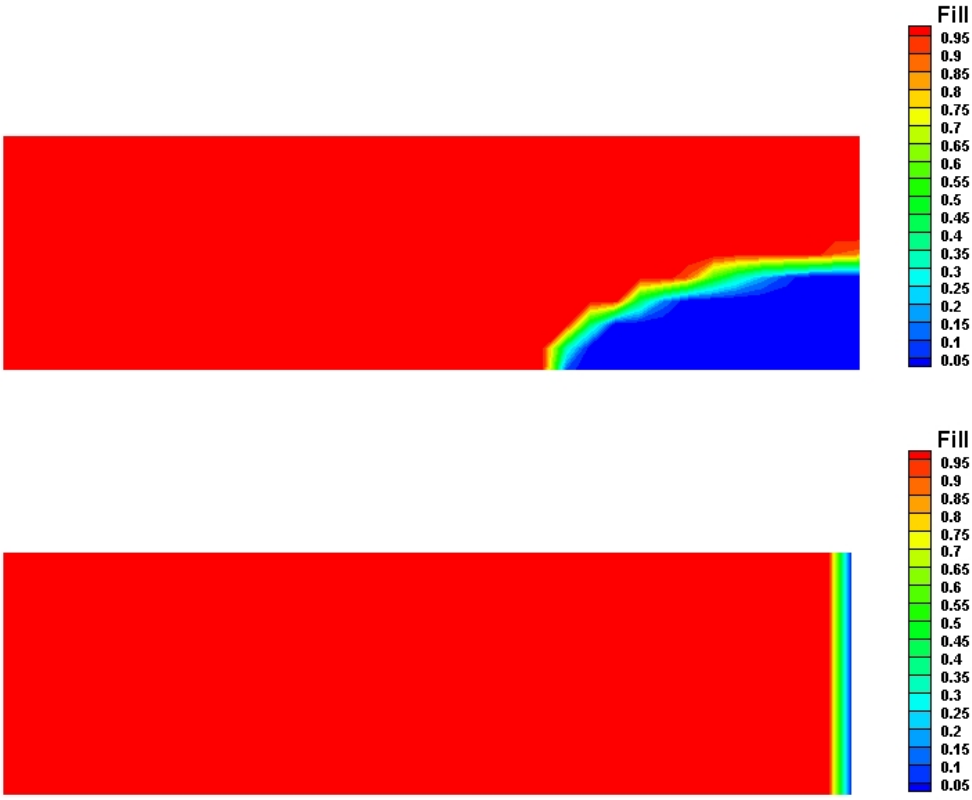

Figure 3.4. Comparison of case 13 (top) and case 16 (bottom) fill factor distribution at the instant where the resin reaches the exit for the first time

Effect of viscosity on filling stage of LCM process is investigated in Figure 3.5. Case 13 and 16 are selected among the 16 possible race tracking scenarios, and the flow distribution with time is investigated for each type of viscosity adaptation whereas the gate locations are the same as pervious. It is demonstrated in Figure 3.5 for the simple mold geometry the flow distribution in both type of viscosity adaptation are almost the same for each of the selected race tracking scenarios. As a result, the accurate viscosity adaptation for simple mold geometries may give the same results as constant viscosity adaptation. on the other hand, the void content at the end of filling process is the same for both type of viscosity since the filling process simulation for each case is run until the pressure at the outlet gate remain zero.

(a)
(b)

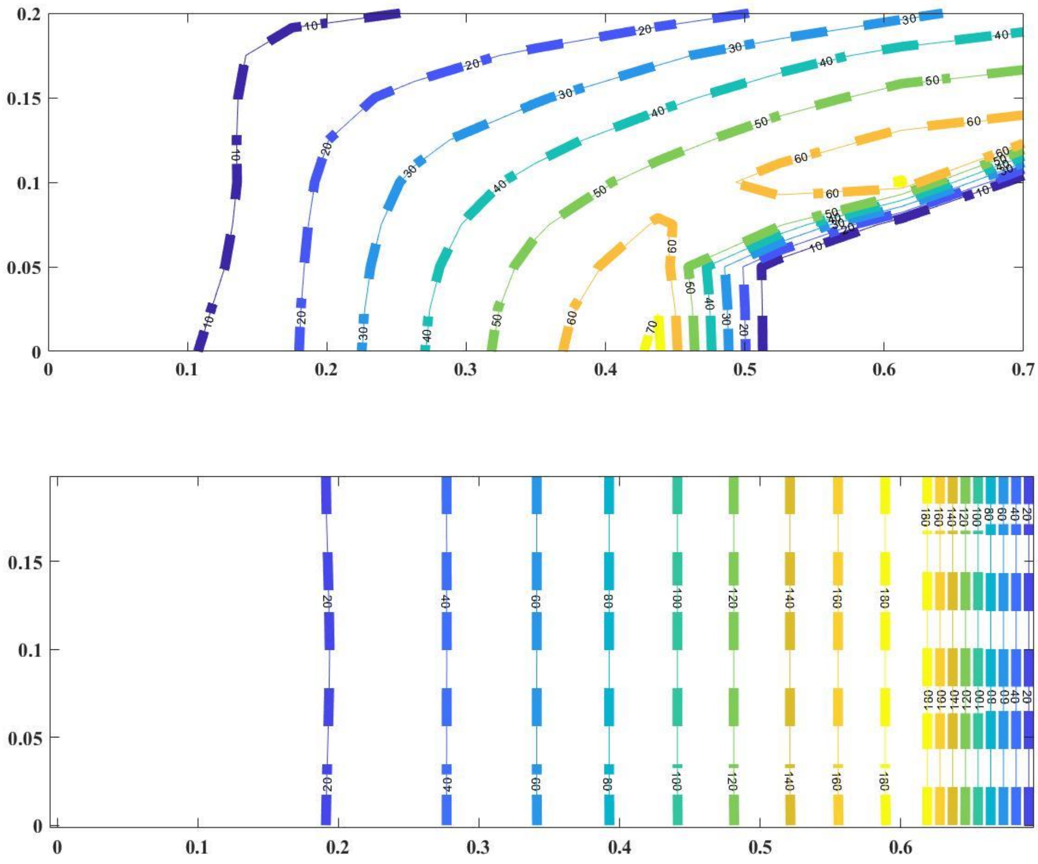

Figure 3.5. Flow front position for (a) μ=0.0259 and (b)μ=0.0259+0.00004t for two race tracking scenarios (13 and16)

3.2.2 Viscosity Effect in 2-D L-Shape Mold Geometry

The viscosity adaptation is investigated for other mold geometries. For the given mold geometry in Figure 3.6. As presented in Figure *3.6*. four edges are considered as the parts of the mold that race tracking may happen means that total race tracking scenarios are 16. The optimum gate location is presented and for the given gates among all possible race tracking scenarios, three case are chosen and the flow propagation with time is shown for two types of viscosity adaptation. For case a which has no race tracking the flow distribution with time for both viscosity adaptation is almost the same. However, for the case b with race tracking in two edges of the mold, flow front position in each time step is different for each of viscosity adaptations.

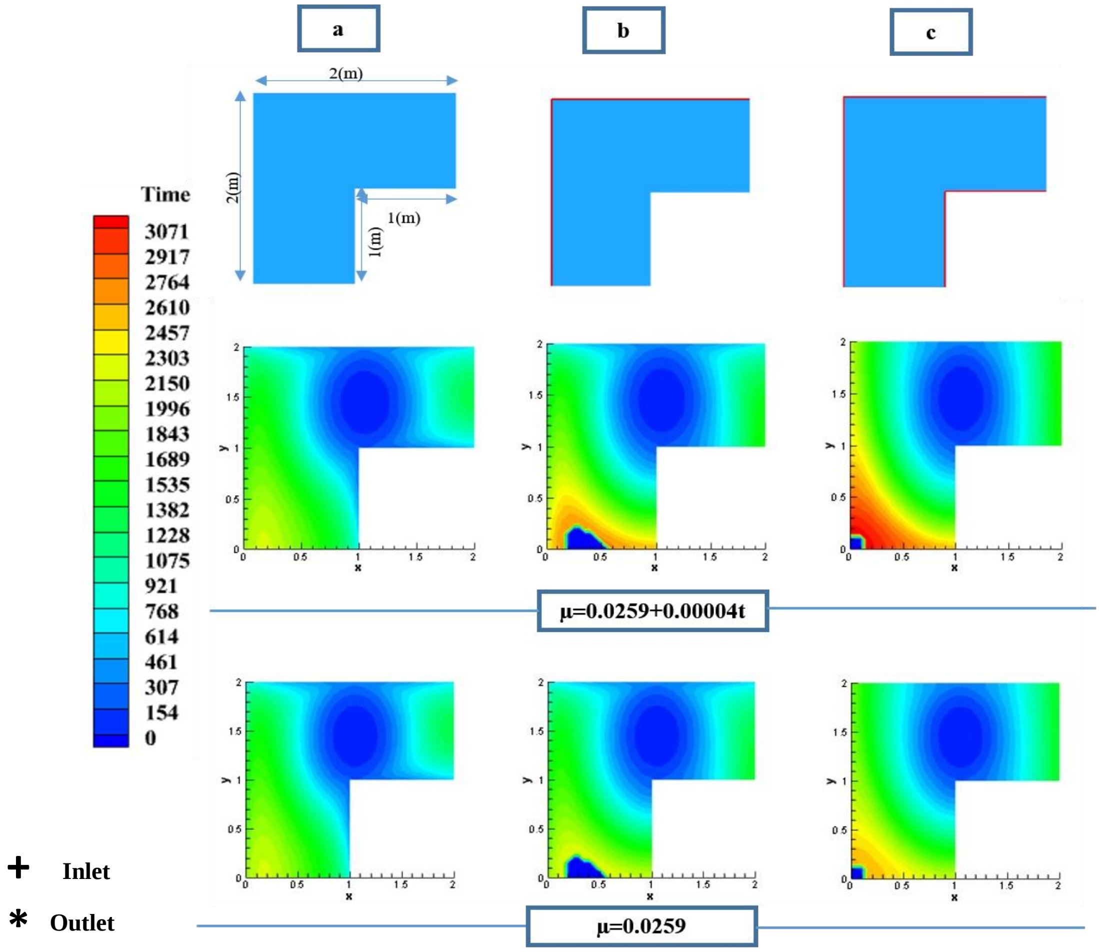

Figure 3.6 flow distribution with time for three possible race tracking scenarios

The third column of Figure 3.6 presented case c with race tracking in 4 edges of the mold. It is shown that flow front position in each time step is different for each of viscosity adaptations and it is more considerable than previous cases.

Variation in flow front position in each time step between each viscosity adaptation lead to different fill time and it may lead to exceeding the gel time of the resin or desirable manufacturing time.

3.2.3 Effect of Viscosity in 3-D Mold Geometry

In order to investigate the effect of viscosity in complex mold geometry. The optimum gate location is adapted for single inlet and outlet implementation in the given mold in Figure 3.7. and flow distribution with time is presented for the case without race tracking consideration. It is shown in Figure 3.7.a that fill time for μ=0.0259+0.00004xt Pa.s is about 13694 seconds however, for μ=0.0259 Pa.s fill time is about 7369 seconds Figure 3.8.

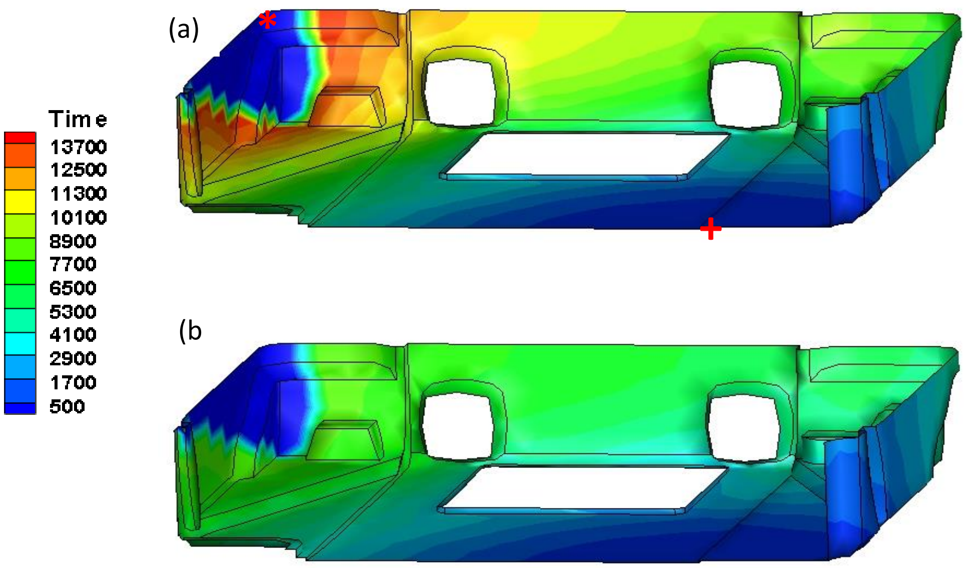

Figure 3.7. Flow distribution with time for (a) μ=0.0259+0.00004xt Pa.s (b) μ=0.0259 Pa.s without race tracking

Also fill time for both cases are below the gel time limit, but for other types of resin with smaller gel time or high production rates, the variations between fill time for accurate and constant viscosity adaptation is problematics. In order to investigate the effect of viscosity in accurate filling condition by assuming possible race tracking scenarios, Figure 3.8. presented the flow distribution with time for the case with race tracking around the holes of the mold. Figure 3.8.a presented the flow distribution with time for μ=0.0259+0.00004xt Pa.s is about 10485 seconds, however it is decreased to about 6242 seconds for μ=0.0259 Pa.s. Also race tracking phenomena decrease the fill time due to speeding up the flow near the edges of holes, but the fill time variation for two types of viscosity adoption is considerable.

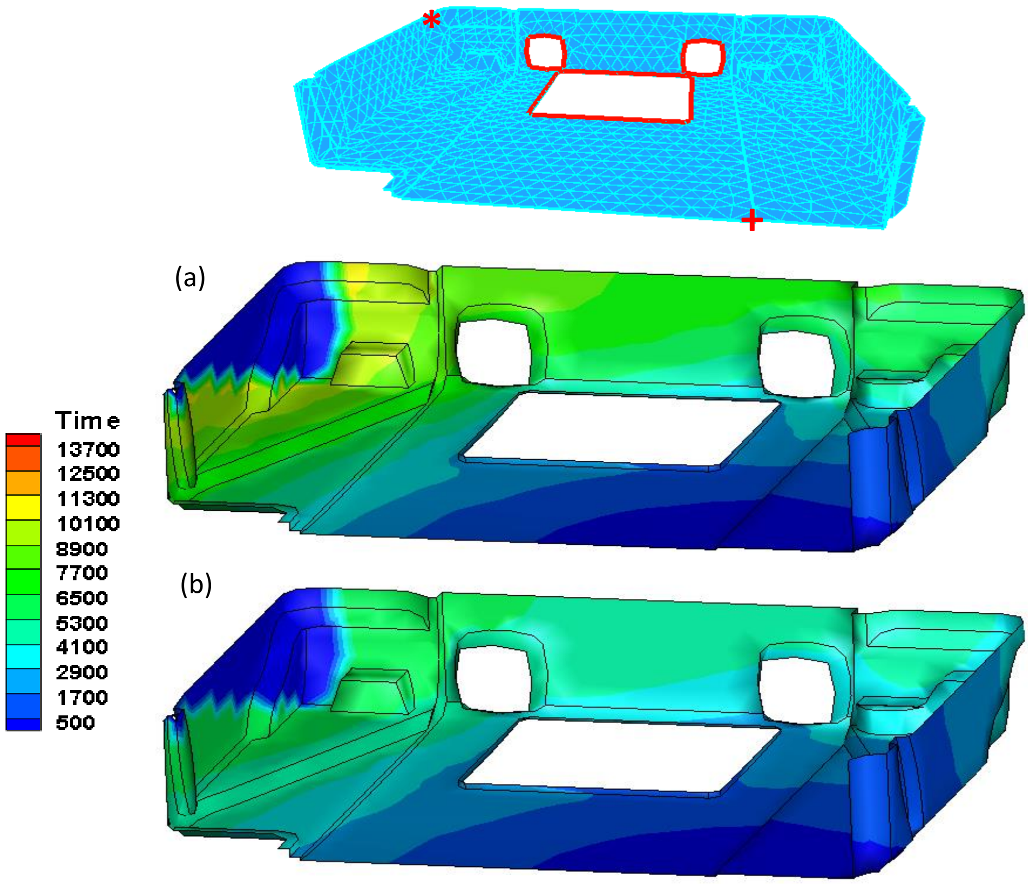

Figure 3.8. Flow distribution with time for (a) μ=0.0259+0.00004xt Pa.s (b) μ=0.0259 Pa.s

As a result, it can be concluded that for simple 2-D types of mold without any inserts and holes, the accurate and constant viscosity adaptation doesn't have considerable effect in terms of fill time of the resin system. However, for nonuniform and complex mold geometries, the viscosity parameter adaptations can totally alter the fill time. The variation in fill time with different viscosity adaptations is even more significant for the cases that, accurate viscosity adaptation exceeds the limits of gel time of the resin system. In other words, the numerical simulation for void content and fill time isn't correct anymore if the fill time exceeds the limits of gel time. Furthermore, for the cases that fill time is under the gel time limits the variation in fill time can lead to tremendous problems in high production rates.

3.3 Multi Inlet and Outlet Optimization

The optimum gate location is adapted to the complex mold presented in Figure 3.9. as multi inlets and outlets and flow front distribution with time is shown.

The optimum multi gate locations is investigated for accurate viscosity adaptation (left side). The same gates are adapted to investigate the resin flow distribution with time for constant viscosity (right side). Furthermore, it is shown in Figure 3.9. a and b that fill time for each type of viscosity adaptation is different. Case a is presented as the case with maximum fill time. For $\mu=0.0259+0.00004xt$ Pa.s the fill time is 2200 sec however for $\mu=0.0259$ Pa.s the fill time is 1763 sec. Case b has the maximum void content among 64 possible scenarios and the fill time for $\mu=0.0259+0.00004xt$ Pa.s and $\mu=0.0259$ Pa.s are 1792 sec and 1583 sec respectively.

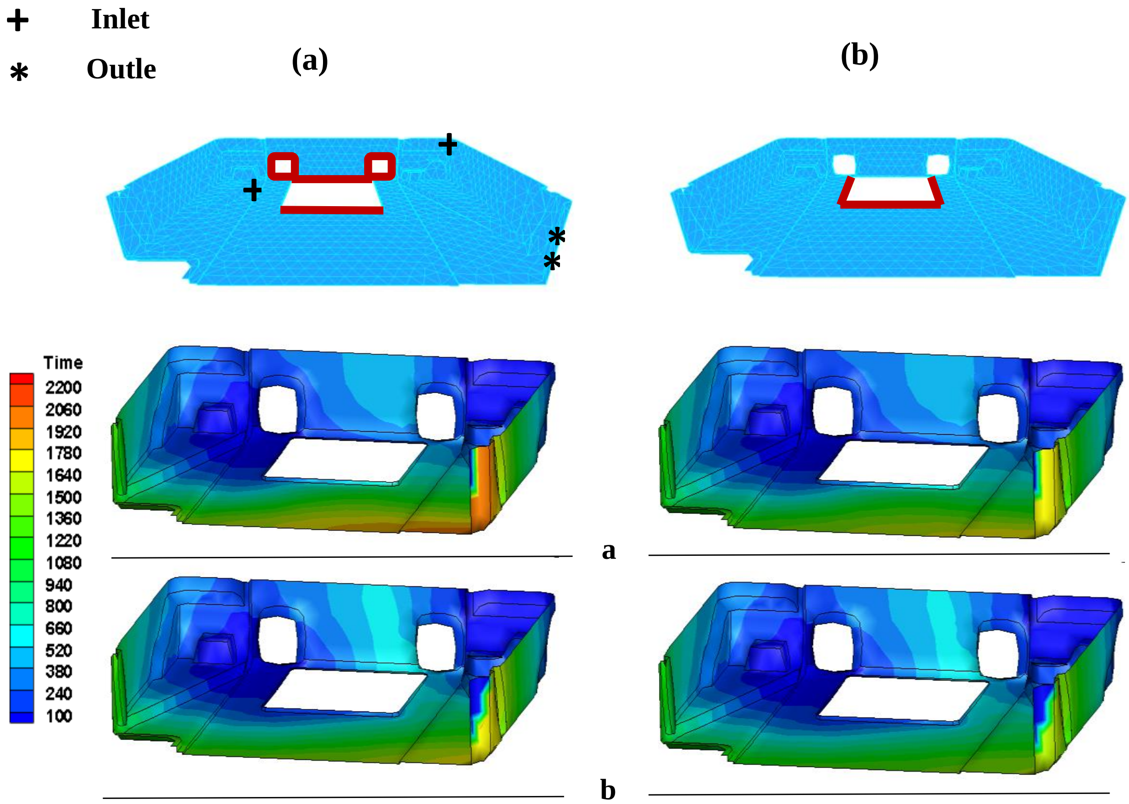

Figure 3.9 Flow distribution with time for two type of viscosity adaptation, µ=0.0259 Pa.s (right side) and µ=0.0259+0.00004xt Pa.s (left side)

It is shown that multi gate adaptation decrease the fill time significantly comparing the The resin flow pressure distribution is investigated in Figure 3.10. for the same gate and vent locations and race tracking configuration presented Figure 3.9. Pressure of the inlet gates are set to 3.0×10^5 (Pa). The resin continues to fill the mold until the pressure at outlet gates remains zero (Pa). Fill factor distribution after the mold is completely filled with the resin is shown in Figure 3.11. The gate locations and race tracking configuration are the same as figure 3.10. The fill factor is assigned to each node in the mold domain. The maximum fill factor is 1. Fill factor between the range 0.9 and 1 represented that the node is completely filled. Thus, the void percentage which is the ratio of the empty nodes to total number of nodes for the case a and b is about 0.5% and 0.9% respectively. The empty percentage smaller than 2% is acceptable for manufacturing purposes.

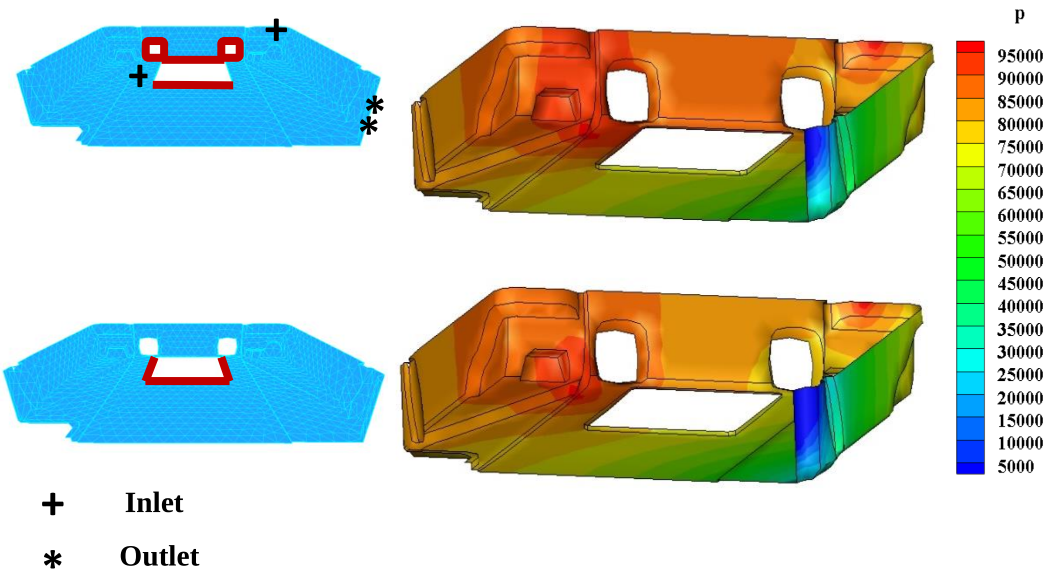

Figure 3.10. Pressure distribution in the mold domain with time

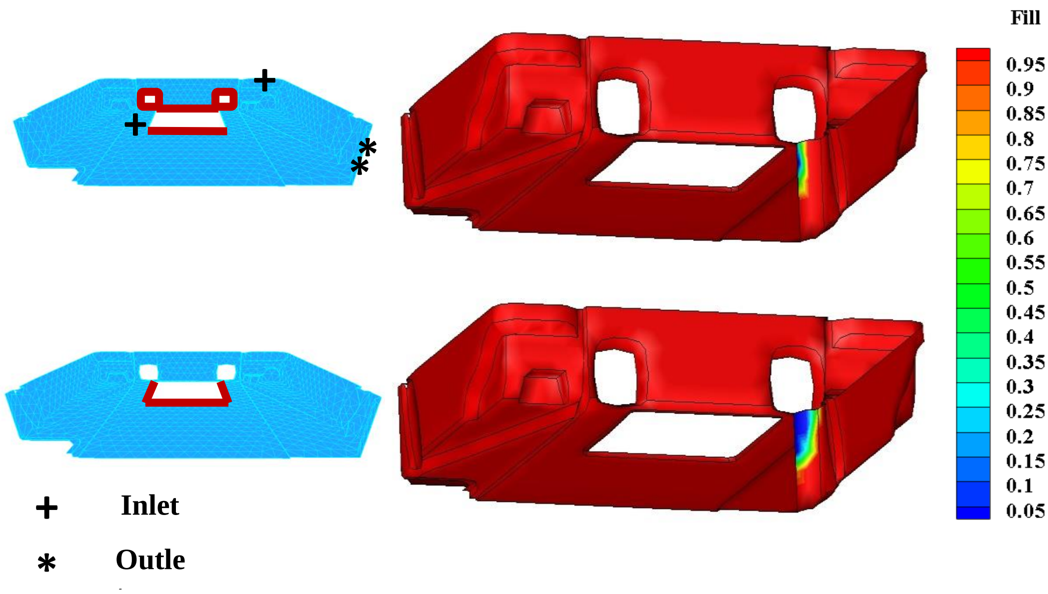

Figure 3.11. Fill factor distribution after the mold filling is completed

3.4 Distribution Media

3.4.1 2-D Distribution Media Design in 2-D Mold Geometry

The final part of the results presented as DM optimization, the optimum arrangement of DM is applied for 0.5% and gel time as the allowable limits for void content and fill time. To safeguard the optimization problem solution, the examined design accepted as the optimum DM design if the fill time and void content as the objectives of the problem examined for all possible race tracking scenarios and satisfied with worst scenario of race tracking while accurate types of viscosity is adopted to the problem. Figure 3.12 presented the optimum DM design for the L-shape mold. The region is started to divide to sub regions(2k), 2k represent the number of sub regions and k starts from 1.

For the first trial the region is divided to two sub regions and distribution media layout is added to each of the regions and examined for all race tracking scenarios, results for void percentage is presented for accurate viscosity adaptation as presented in Table 3.1. It is shown in Figure 3.12 single layout of distribution media satisfies the allowable limits of objective function. In other words, implementation of DM layout in left side of the mold decreased the void content of all race tracking scenarios below the 0.5%.

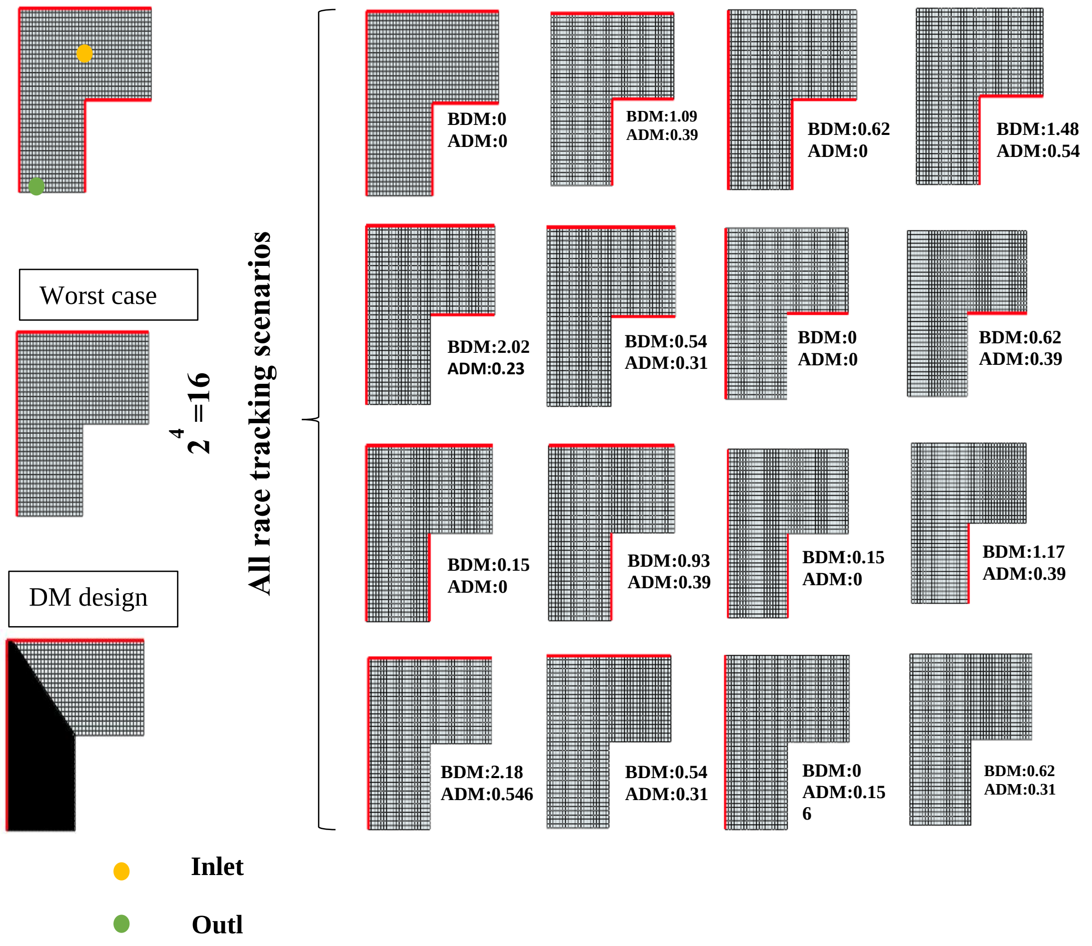

Figure 3.12. Void content of all race tracking scenarios before DM implementation and after optimum DM design

3.4.2 Distribution Media Design in 3-D Mold Geometry

The distribution media (DM) implementation is adapted for complex geometry presented in Figure 3.13. The optimum gate locations are investigated and adapted to the mold geometry in the first stage. Figure 3.13. b represented the flow distribution with time for the given scenario in part a. The second stage of optimization as optimum DM implementation is adapted to the mold with optimum gate locations. As presented in Figure 3.13.c the mold geometry is divided to 10 regions and DM layout is added to 2 of the regions as a result void content and fill time decreased to 0.42% and 1.34e3 respectively. Flow distribution with time is shown for the worse scenarios of race tracking for the same gate locations.

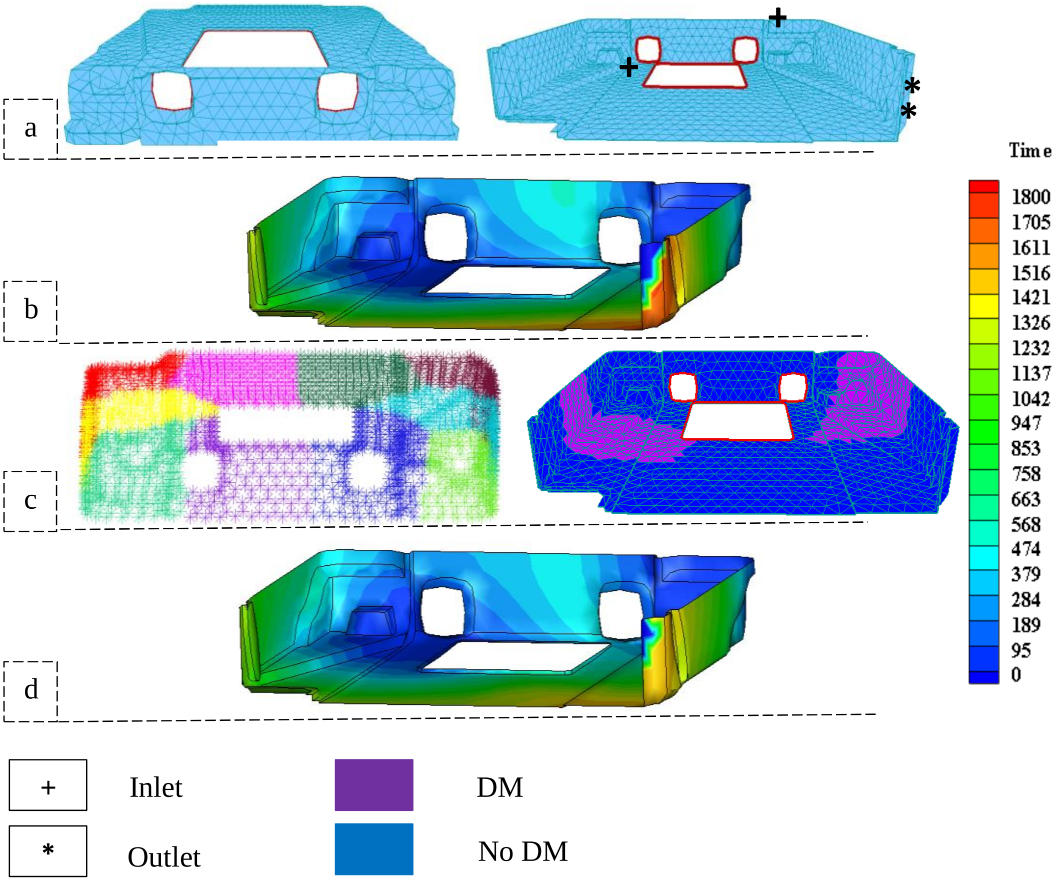

Figure 3.13. Two stage optimizations for complex geometry (a) race tracking channels (left side), inlets and outlets locations (right side), (b) resin flow distribution with time for optimum gate adaptation. (c) region division (left side), distribution media (DM) implementation

3.5 Viscosity Effect in Distribution Media Design

It is presented in Figure 3.14, the optimum DM design is investigated for same inlet and outlets as presented on Figure 3.14. The optimum DM design is investigated using accurate viscosity and constant viscosity adaptation in Figure 3.14. a and b. It is presented in Figure 3.14.a that the mold region is divided to 22 sub regions and the optimum design is achieved by adding 4 distribution media layouts however, optimum distribution media design is completely different for constant viscosity adaptation and the region is divided to 11 sub regions. The objective function limits are satisfied by adding 4 distribution media layouts with different sizes in different locations of the mold. It is important to notice that the limits for objective function in both type of viscosity adaption are the same.

The objective for void percentage of both types of viscosity adaptation is considered as 0.5% for the worst scenario of race tracking and the fill time limit is considered as 1000 seconds.

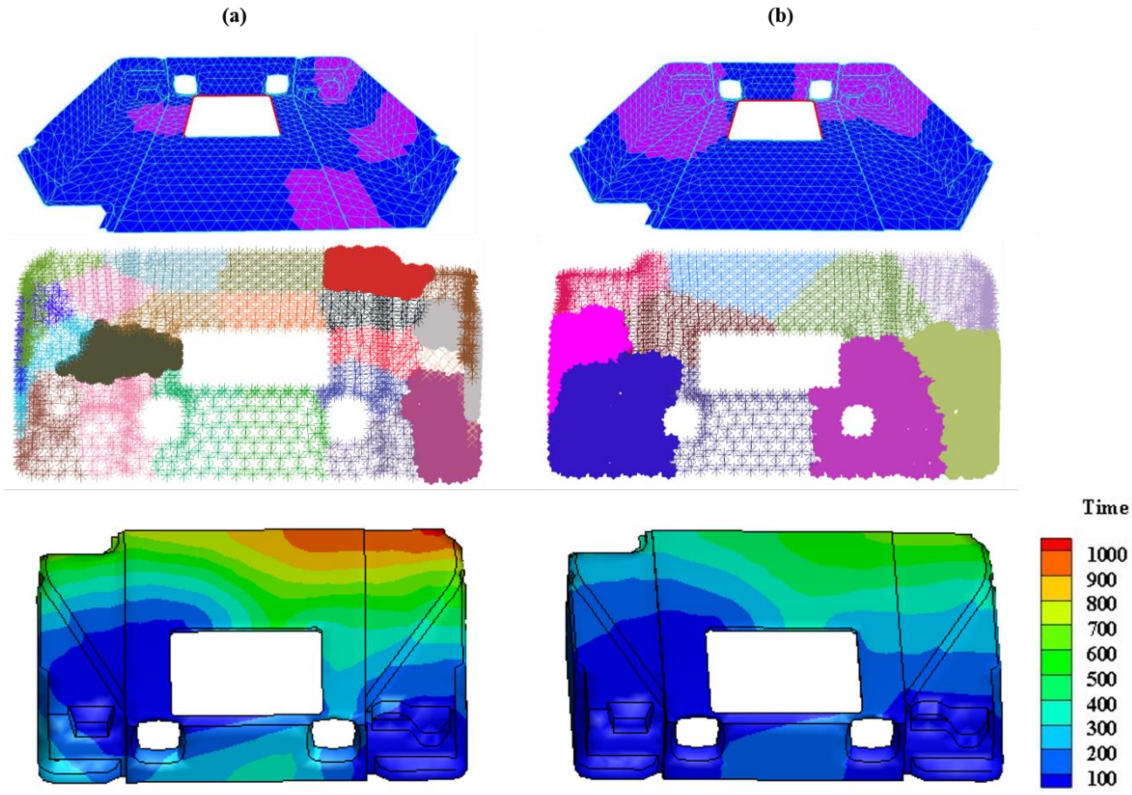

Figure 3.14. Optimum distribution media (DM) design: (a) for μ=0.0259+0.00004t and (b) for μ=0.0259.

4 SUMMARY AND CONCLUSION

This study investigated the Liquid composite molding (LCM) process modeling and optimization. Also, the effect of process parameters such as viscosity and race tracking is investigated in both modeling and optimization steps. Liquid composite molding (LCM) process is modeled using Liquid Injection Molding Simulation (LIMS) software which is developed at the university of Delaware. The effect of race tracking and viscosity is investigated in flow impregnation simulation. It is shown that resin impregnation pattern in the fiber preform changes for different race tracking scenarios. This change is described both in terms of fill time of the resin and void formation during the filling stage of LCM process. Viscosity is assumed as another parameter effecting the filling process. Assuming an isothermal process the filling process simulation is investigated for constant and variable with time viscosity parameters. Fill time is investigated for both type of viscosity adaptation. It is concluded that for simple 2-D mold geometries without inserts the accurate viscosity adaptation doesn't have significant effect in fill time. However, for complex and 3-D mold geometries the fill time variation is considerable, and it may be problematic in high production volumes. As a result, in order to have accurate filling process simulation, the filling process is simulated for all possible race tracking scenarios and viscosity is adapted as a variable with time parameter. Modeling of the process is considered as the preliminary step for optimization of LCM process. Inlet and outlet gates locations is considered as design variables in optimization problem. Genetic Algorithm used to optimize the gate locations. The resin flow simulation is investigated for all possible race tracking scenarios and accurate viscosity adaptation in each step of GA. And the given answer by the GA ensure the minimum fill time and void content among the worst scenario of all GA gates trials. The minimum fill time and void content limits are user defined values the only constraint is to set fill time to any number smaller than resin gelation time. Also, the void content smaller that 2% is accepted. Another step of optimization is considered for further relaxation of gate optimization. Distribution media optimization is considered as the second stage of optimization. Using this one could further reduce the fill time and void content given in the first stage of optimization or assuming higher limits of void content and fill time in the gate optimization can be completed by optimum adding of distribution media layouts. This way decreases the complex and heavy computational procedure in gate location optimization specially for complex mold geometries. The optimum distribution media design guaranty the minimum void content and fill time for all possible race tracking scenarios for the given gate locations executed from first stage of optimization. The effect of viscosity is investigated in distribution media optimization stage. It is concluded that for user defined values of fill time and allowable void percentage limits, the optimum DM design is different in terms of number of DM layouts and their position for each type of viscosity adaptation.

4.1 Future Work

Following this dissertation, one could investigate the optimum gate locations considering the effect of more parameters as design variables. Injection pressure, optimum number of gates, viscosity as a function of temperature assuming non isothermal filling process could be added to design parameters. The optimum design variables can be investigated for thermoset and thermoplastic resin types using experimental setup. Optimum distribution media design considering both the locations and number of distribution media layouts can be added to design variables of optimization problem. The filling process can be modeled assuming through thickness permeability to ensure the accuracy of the achieved result specially for VARTM types of processes.

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