FLOW SIMULATION OF THE RESIN TRANSFER MOULDING PROCESS

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ABSTRACT:

In recent times, vacuum-assisted resin transfer molding (VARTM) has become a promisingtechnique for the processing of large composite structures. On the contrary, there are few issues related to VARTM processing as many process parameters are involved and required to optimize them to achieve high fiber volume fraction containing composite material. These issues can be addressed and resolved by an understanding of various flow modeling techniques and simulation methods. In this present study, a review of different approaches in flow modeling and simulation of the VARTM process is presented. The processing technology of VARTM along with the fundamental and constitutive models for mold filling stage as well as curing stage such as permeability, compaction, resin viscosity and cure kinetics are presented. The numerical simulation methods adopted by various researchers used to simulate the filling processes with their specific applications and simulation software are also reported and reviewed. As an outcome, identification of permeability of various fibers and simulation processing time are more predominant factors to perform accurate VARTM simulation.

1. INTRODUCTION

Polymer matrix composites (PMC) are becoming the prime choice in the category of material to replace metals and other materials in numerous sectors such as aeronautics, automotive, sports industry, construction, and marine structures. Composite structure also gives benefits in terms of reproducibility, quality, performances, environment friendliness and cost reduction, which are the indication of increasing the demand in the recent market. Among the various primary manufacturing processes for composites, Liquid Composite Molding (LCM) processes, for instance Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM) are more suitable for processing complex shaped composite with a good surface finish and quality. Unlike the RTM process, VARTM provides significant reduction in the tooling cost as it requires a mold and a vacuum bag is used to close the mold. Therefore, manufacturing large composite structure such as ship hulls, windmill components and turbine blades, etc., VARTM is considered as the most cost-effective manufacturing method [1,2]. However, VARTM process can be critical, as it is required to complete the mold filling with adequate wetting of the fiber mat to achieve high fiber volume fraction in the composite. Incomplete resin infusion in the mold causes dry spots and resulted in defective parts. To accomplish good quality product, processing parameters, such as the locations and numbers of injections and vents need to be correctly set [3]. This problem can be addressed and understood by using mold filling simulation tool, allows the prediction of mold filling time, air trapped zones, resin flow around the inserts which probably lead to unfilled regions, etc [4]. Based on this, the VARTM process technology is discussed and formulated the VARTM model. In the present work, VARTM model and its implementation in the numerical simulation tool for creating a variety of real part by the contribution of various

1.1 VARTM Process Technology VARTM is a variation of the RTM infusion process. VARTM is gaining wider acceptance as it allows for good control of the fiber-to-resin ratio and provides consistent fabrication process for large structures at reasonable cost. In the VARTM process, dry fabric sheets are placing into a mold, covered via a flexible vacuum bag with the use of adhesive sticky tapes, which will govern the vacuum inside the mold cavity by pulling a vacuum. At the same time, polymer resin is infused to saturate the dry fibers until the resin is fully cured [5]. The schematic representation of VARTM is shown in figure 1.

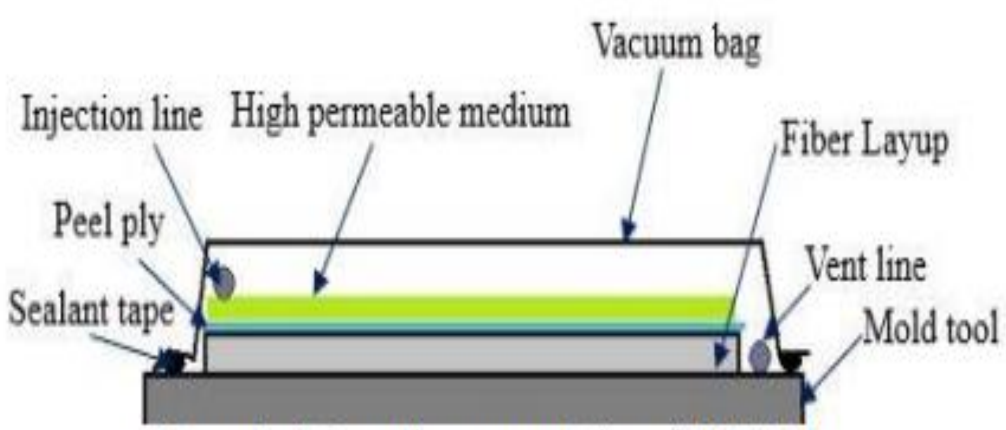

Figure 1. Schematic representation of VARTM

The VARTM process can be divided into five stages. To begin with, in premolding stage, the mold surface is cleaned. Then the mold release agent and the gel coat are applied onto the mold tool respectively. Next, dry fiber mats are placed into the mold to create fiber layup (fiber reinforcement stacking). To produce adequate resin flow, high permeable medium is placed over the fiber layer stack up and then covered by a flexible vacuum bag. The cavity formed by the vacuum bag is sealed through vacuum sealant tapes. Resin can be injected into the fiber mats form one side by creating a vacuum inside the mold cavity. Once the cavity is filled with resin, then resin will take time for curing in room temperature condition or under the preheated environment. Finally, the cured composite part is taken out with the help of peel ply. Although this process seems simple, in real time fabrication, the process can be quite complicated. The selection of the injection line and vent line location must be carefully designed so that the mold can be completely filled with resin [3,5].

2. FORMULATION OF VARTM MODEL

The VARTM process has to deal with two fundamental models: resin flow through the fiber layup, and compaction and relaxation of the fibers under the vacuum condition. In addition to this, the resin cure kinetics and viscosity must be identified to confirm whole resin impregnation of the fiber layup before gelation of the resin. A complete simulation model involves three constitutive models: the resin flow in the fiber layup, the compaction of the fibers during the infusion practice, and the viscosity and cure kinetics of the resin [1,6]. *2.1 The fluid flow model* This model is developed to trace the resin flow through the high permeable medium and the fiber layup. The governing equation for the flow of incompressible resin considering as a quasi-steady state can be described by following continuity equation,

$$\nabla u = 0 \qquad (1)$$

Generally, flow through the porous media can be modeled using Darcy's law equation (2),

$$u = -\frac{K}{\mu} * \nabla p \qquad (2)$$

In this equation (2), the fluid velocity u is related to the resin viscosity μ, pressure gradient p and the

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In this equation (2), the fluid velocity u is related to the resin viscosity μ, pressure gradient p and thepermeability K. The key challenge is to determine the permeability in modeling the VARTM process. There are two methods generally used in determining the permeability of a fiber layup likely as the steady-state and advancing flow front methods. *2.2 Compaction of fibers during infusion* In VARTM process, the flexible vacuum bag is used to provide compaction pressure. In this model, two different processes simultaneously occurred. First, creation of vacuum inside the mold cavity by pulling a vacuum and resulted into variation in the pressure across the vacuum bag. Second, this effect allows the infusion of resin in the mold cavity. Hence, this flexibility of vacuum bag allows to vary thickness of the fiber layup during infusion as a function of resin pressure [5,7]. The compaction of the fiber layup is difficult and depends on the compressibility and relaxation of the fiber layup under pressure, and the interaction between the fibers and the resin flow. The compaction pressure on the fiber layup can be calculated using equation (3) as shown below:

$$P_{atm} = P_{comp} + P_{resin}$$

where *Patm* is the atmospheric pressure outside of the mold cavity, *Pcomp* is the compaction pressure applied to the fiber layup, and *Presin* is the resin pressure. This phenomenon is shown in figure 2.

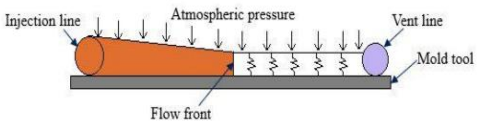

Figure 2. Variation in compaction pressure experienced by fiber layup due to resin pressure

As the resin pressure increases, the corresponding compaction pressure decreases in the fiber layup as per the equation (3). This effect causes the reduction in the fiber volume fraction. Robitaille et al. [8] has been described an empirical power law equation (4) for the relation between fiber volume fraction vf of laminate composite with initial fiber volume fraction $vf0$ and compaction pressure *Pcomp* at 1 Pa. Here *B* is the compacting stiffness index (*B*< 1).

$$v_f = v_{f_0} P_{comp}^{B}$$

2.3 Permeability Model Another key characteristic to VARTM process modeling is the selection of the right permeability model. As with the effect of compaction pressure on fiber layup, the spacing between individual fibers decreases and flow passages are confined. As the resin is passed forcibly through smaller and smaller spaces, the pressure drops in the resin increase leading to a decrease in permeability. Due to local compaction pressure, deformation of fiber alignment can take place, which results into fiber permeability also varies with the fiber volume fraction [1,5,6]. The most common and simple form of permeability relation is the Kozeny-Carman model equation (5) given by [9]: $K = k\frac{(1-v_f)^3}{v_f^2}$

Where the Kozeny constant *k* is determined experimentally and depends on the fiber geometry. By combining equations (4) and (5), it is possible to acquire permeability as a function of compaction pressure.*2.4 Resin Model* As the VARTM process in the advancement mode, the resin starts to cure and changes in the viscosity. Therefore, the major challenge is the resin gelation before the completion of the infiltration process mainly for large parts. Hence, the resin model is become essential to forecast the resin cure time and viscosity variation of the resin. A typical expression for the resin cure kinetics model is given in following equation (6) [10] $\frac{d\alpha}{dt} = f(T,\alpha)(1-\alpha)^n$ Where, *dα/dt* is well-defined as the cure rate, *α* is the degree of cure, *T* is the resin temperature, *f(T,α)* is a function that depends on the reaction type, and *n* is the reaction order. The resin cure rate is a function of resin temperature and degree of cure. Differential scanning calorimetry and differential thermal analyzer are two common method to develop the kinetic model. If the resin viscosity is available in terms of position and time, then resin infiltration process can be accurately predicted. Resin viscosity is a complicated function of shear rate, degree of cure and resin temperature. The viscosity model normally used was developed by Castro et. al. [11]

$$\mu(T,\alpha) = \mu_0(T,\alpha)\left[\frac{\alpha_g}{\alpha_g-\alpha}\right]^{A(T)+B(T)\alpha}$$

Where, *μ* is the viscosity, *μ0* the viscosity at zero shear rate, *T* the temperature, *αg* the degree of cure at gel, *α* the degree of cure, and *A* and *B* are parameters which depend on the resin temperature [6].

3. LITERATURE REVIEW BASED ON VARTM FLOW MODELING AND SIMULATION

The aim of the literature review is to address the research trends within the fields of mathematical flow modeling and simulation of the VARTM process. In this regards, various research articles have been found in relation to mathematical flow modeling and its implementation in the numerical simulation method for the VARTM process. Following table 1 represented the contribution of different researchers in the field of determining the unknown parameters for VARTM process and its possible flow simulation methods.

Table 1. Literature review on VARTM for flow modeling and simulation technique.

Sr. No.	Author	Year	Contribution
1.	K. Han et. al. [12]	2000	simulated the VARTM process with proposed hybrid 2.5 D and 3D flow model. They have considered two issues: the resin flow from the injection gate to the fiber mats, and the compaction pressure over the fiber mats. Based on the simulated results, scalable model of ship hull fabricated and found that simulated results well agreed with the VARTM infusion experiment.
2.	M. K. Kang et. al.[13]	2001	developed analytical model for the VBRTM process with the inclusion of force equilibrium between fiber and resin. In this study, the authors have carried out the mold filling simulation through multiple resin inlet ports with various vacuum conditions for the midship section of battleship. Developed simulated model has additional features of final part thickness after resin curing and formation of dry spots containing air.

Sr. No.	Author	Year	Contribution
3.	X. Song et. al. [6]	2003	evaluated the effects of the high permeable medium on resin infusion and different high permeable medium configurations were examined and compared the data for resin infiltration. Further they have also described various sub models for curing of the resin, variation in resin viscosity due to curing effect, resin flow through the fiber layers and high permeable medium and compaction of the fiber stack during the infusion. Here, the authors have concluded the resin infiltration scheme denoted in Model – III gave reasonably good estimation using FE-CV numerical simulation method.
4.	J. Dai et. al.[2]	2003	investigated the advantages and disadvantages by using the high permeability layers and adding inlet tubes in the core for the sandwich panels. They have taken design parameters as number of layers of high-permeable medium and the number and size of inlet channels for reducing the mold filling time. They have carried out optimization for reducing the cost and time through simulation technique using RTMSIM (finite element code) and experiment. It is found that the high permeable layer method offers the advantages of both lower cost and shorter manufacturing time.
5.	R. Johnson et. al.[14]	2003	studied on a system, which considered the effect of fluid motion and voltage control of an induction coil, results into viscosity reduction. Hence, it establishes the permeability variation in the VARTM process. It is implemented in a simulation framework for non-isothermal flow of the VARTM process with the presence of induction heating. The basic energy balance equation is used to estimate material temperatures and forecast future coil voltages that would limit maximum material temperatures.
6.	J. Acheson et. al.[15]	2004	investigated the effect of compaction over fiber layers and saturation of fiber tows during filling process. The governing equations for describing the resin flow by non-rigid control volume. They found that the variation in fiber mat permeability is modified due to the changes in the fiber volume fraction due to changing compaction pressure. Further, it is well observed that the resin pressure curve can be significantly altered with and without compaction.
7.	R. Chen et. al.[16]	2004	introduced a new approach of equivalent permeability for reducing calculation time in VARTM flow simulation of large parts. This method increases convergence efficiency and simplify the flow model of the CV/FEM simulation. Further, proposed method is also validated with a case study of automobile part and its results indicated well agreement with the VARTM experimental fill time and fill pattern.
8.	K Hsiao et. al.[17]	2004	developed genetic algorithm/simulation-based design methodology for optimizing the flow distribution system. In this study, use of high permeable medium layup and inlet flow arrangement in VARTM is presented. The proposed design is used to manufacture co-cured rib structure using trial and error approach and suggested GA/simulation-based methodology. Good agreement has observed between experimental and flow simulation results. This novel technique can be used for complex manufacturing of composite parts.

Sr. No.	Author	Year	Contribution
9.	A Gokce et. al.[18]	2005	developed the algorithm for estimating the permeability of the high permeable medium (HPM) and the fiber layup simultaneously from a single experiment. In this research, the HPM permeability was investigated as a function of the fiber lay-up and concluded that it varies with the fiber lay-up. One of the VARTM simulation tool LIMS is used to estimate the permeability values by incorporating the developed iterative algorithm.
10.	M. Grujicic et. al.[19]	2005	developed CV/FE model to evaluate the infiltration of fiber layup with non-isothermal resin for VARTM process. Simulation of infusion process is governed by proposed CV/FE model and optimize it for minimizing the filling time as non-isothermal resin changes its viscosity with the application of high temperature. It is observed that effect of tool-plate heating leads to an increase in the rate of infusion. Optimization analysis results shown that in order to take benefit of tool-plate heating, 70% to 80% of the mold needs to be filled with the resin at the room temperature before heating of the tool-plate.
11.	S. Walsh[20]	2005	Due to the change in part thickness during VARTM, leading to undesirable reduction in mechanical properties. This mainly depends on the levied pressure value and the fibrous material behavior. Therefore, the author has developed the numerical model, which gives equilibrium relationship between restraining pressure, fibrous material response, and internal resin pressure employed by implicit finite element-based process. This analytical model verified with the 1D rectangular strip and circular disk illustrations, as it is inexpensive to apply. Experimental work is not included so not compared with the numerical model.
12.	A. Khattab[21]	2005	developed virtual flow model using CVFDM for VARTM process design. According to proposed flow model, animation of flow pattern, pressure distribution inside the mold and evolved voids can be extracted by combining the image file with the help of graphic interchange format. Several case studies have been carried out for the resin flow simulation. The results shown close agreement between the flow model and experimentation results.
13.	C. Dong[3]	2006	presented the equivalent medium method (EMM) for very fast and accurate simulation of 3-D models as it is hiving two distinct flow media (High permeable medium & fiber layup) which takes more computation time and cost. In this method, thickness of HPM is equally considered to fiber thickness by applying equivalent material properties. With the use of EMM, the simulation time can be reduced by 85% with acceptable accuracy. He also suggested that EMM is more improved technique than equivalent permeability method (EPM) which is not considering the porosity of HPM and through thickness permeability.

Sr. No.	Author	Year	Contribution
14.	C. Dong[22]	2006	developed new approach provides basic recommendation for VARTM process design and optimization. In this study, they have used dimensionless process variables as thickness of fiber layup, permeability, RTM mold-filling time, and porosity. According to DOE (Design of Experiment) methodology, significant process parameters were identified and with the use of RSM (response surface method), quadratic regression model was developed. Present model is validated using ship hull and car hood examples by simulation and experiments. It is also observed that there is significant reduction in the computation time.
15.	P. Simacek et. al.[23]	2006	examined the additional body forces such as gravity forces in simulation of resin infusion in LCM. Author has presented the weak formulation and FE based approximation. In this paper, examples such as 1-D vertical filling, 2-D vertical plate with central injection and with a high permeable medium to manufacture a vertical panel are presented. It is also verified the same by comparing the analytical solutions. These examples highlight significance of body forces on the filling time and the flow contours during mold filling.
16.	J. Lawrence et. al.[24]	2007	explored the effect of impermeable embedded inserts in the VARTM process. Inserts are placed inside the fiber layup during the resin infusion stage. Basically, the purpose of additional component placed in the composites is to enhance the intrinsic properties or to enhance additional functionality. This obstructs the flow of resin in the area below the inserted object and can result in resin void areas. Therefore, several case studies have been conducted through numerical simulation to examine the placement of distribution medium and embedded inserts and effect of its geometry (such as length, width, height) with the properties of resin. Experimental demonstration shown that with the use of modifying distribution medium results in eliminating the dry spot. Further, it is observed that certain material and geometric combinations can demonstrate this approach.
17.	J. Lawrence et. al.[25]	2008	taken real world part as upper deck of a helicopter pylon assembly is manufactured by VARTM and demonstrated resin infusion simulation and process monitoring. In this study, flow simulation tool is used for the infusion strategy such as location of infusion runner with optimal location and proposed pathways. Further, the timing of resin arrival into the various ports of the mold is studied and repeatability to the process can be achieved by reducing the chance of error. There is some deviation exists among the simulation and experimental results due to the estimation of the permeability of fibers and simplification in the part geometry modeling.
18.	J. Li et. al.[26]	2008	accounted the effect of thickness gradient due to infusion pressure gradient during the resin infusion in VARTM process. Therefore, they have developed the numerical model by combining CV and VOF methods to solve free surface problems. The authors have also investigated the mechanism of dynamic change in thickness variation during the infusion and curing stages. In this article, the boat deck part was infused by the VARTM and compared with the simulation results.

Sr. No.	Author	Year	Contribution
19.	C. Dong[27]	2008	presented two-step VARTM process simulation method for improving the efficiency. In this study, coupling between the DOE approach and 2-D CVFE method has carried out for VARTM simulation. The equivalent permeability and porosity with different process parameter combinations are calculated. This method is implemented for 2-D mold filling simulation. From the results, accuracy is achieved within 5% along with the saving computation time over 99%.
20.	Y. Song et. al.[28]	2008	modeled analytical solution for the resin infusion process and examined the compaction behavior of fiber layup experimentally. This analytical model also predicts the pressure and thickness distribution during the resin infusion stage. Further, verification of analytical model is carried out by mold filling experiment and simulation. The simulation results well agreed with analytical solutions.
21.	M. Robinson et. al.[29]	2008	introduced VARTM simulation model that considered transient nature of laminate thickness and permeability as a function of pressure. This model is not limited to mold filling but also applicable to bleeding of excess resin, which reflects into fiber volume fraction and final part thickness. It is also seen that the simulation results showed good agreement with experimental study for the infusion stage as well as resin bleeding stage.
22.	P. Simacek et. al.[30]	2009	examined post-filling flow with & without membrane in VARTM by theoretical study. In post-filling flow period, due to deformation of fiber layup the resin flow continues for limited time unless the uniform pressure distribution is achieved. In this study, the developed model for post-filling flow is executed using FDM which utilizes the explicit time integration. As per the results, the prediction time for achieving resin equilibrium condition within the part as well as the final part thickness can be solved.
23.	Q. Govignon et. al.[31]	2010	developed 2.5D RI/VARTM simulation and compared to experiments for three moderately complex fiber layup shapes such as Square-hole, dumbbell &dogbone. The authors have demonstrated the SimLCM tool for the simulation and programmed the extended to post filling period. From the simulation results, it is observed that flow front pattern prediction is accurate as the shape of the thickness distribution. It is also notable that the rise of pressure as the flow front reaches the cutout is more pronounced than in the experiments.
24.	R. Ranjbar[32]	2010	investigated resin infusion strategy for the manufacturing of wind turbine blade with the use of flow simulation tool. In this study, authors have developed 3-D non-isothermal modeling for the VARTM process and verified its requirement by using 2.5-D non-isothermal model and a 3-D isothermal model. Presented model is utilized for optimizing the inlet port arrangement, mold temperature and resin temperature to reduce the filling time. It is also observed that the projected flow contour for the 3-D isothermal model is very comparable to that for 3-D non-isothermal model and the variance between the filling times is moderately small.

Sr. No.	Author	Year	Contribution
31.	R. Du et. al.[38]	2013	simulated and optimized the VARTM process for the case of car bumper beam using RTM-worx software. There were total six optimization schemes used for rapid mold filling by multiple injection ports and vents. It is found that there is lot of saving in the resources and time for conduction of practical experiment.
32.	C. Polowick[7]	2013	conducted the research on improving the VARTM processing parameter weight reduction and recover the strength and surface finish of Unmanned Aerial Vehicle (UAV). He developed the simulation model for the mold filling and resin emptying in VARTM process. In the experimental study, effect of presence of corner on composite thickness, void content and strength is evaluated. He has improved the part quality by using new bagging technique and greater the corner radius with fiber lay-up performance.
33.	C. Kong et. al.[39]	2014	used flax fibers for the manufacturing of chemical container with the aid of VARTML (Vacuum Assisted Resin Transfer Molding Light). They have performed the resin flow analysis of VARTM using RTM-worx flow simulation software. From the simulation results, they have identified to increase the injection pressure for reducing the mold filling time and to avoid resin gel time. In this work, they have also investigated the structural strength of container and ensured for the production of the same.
34.	B. Yang et. al.[40]	2014	developed the novel numerical method to address mold filling simulation of VARI which is based on the analysis of fiber layup compaction and fiber tow impregnation. Further, this work also included effect of the fiber layup deformation and analyzed the unsaturated effect on the mold filling. In this work, VOF method of ANSYS fluent software is used to simulate macro flow. To verify the applicability of proposed approach, three examples are conducted for accuracy and precision.
35.	C. Kong et. al.[41]	2014	investigated the mechanical properties of manufactured flax/vinyl ester composite by VARTM. Chemical tank for agriculture vehicle has been processed using flax/vinyl ester by VARTM. After the successful structural test of storage tank, resin flow simulation for VARTM process has been carried out. The simulation result shown better agreement with the experimental results in terms of resin filling time.
36.	G. Struzziero[42]	2014	developed genetic algorithm based multi-objective optimization methodology for the curing stage and filling stage during the VARTM process. Simulation of curing stage and filling stage problem solved by FEA. In the curing stage, the optimization aims at finding a cure profile minimizing both process time and temperature exceed within the part. In the filling stage, gate locations, the thermal profile during filling, and initial resin temperature are optimized to minimize filling time and final degree of cure. Further, this optimization is resulted in the cost reduction of 500 euro in process design involved.

Sr. No.	Author	Year	Contribution
37.	R. Matsuzaki et. al.[43]	2016	investigated the data integration through visual observation and stochastic simulation of resin flow during VARTM. The data adaption was performed using the four-dimensional asynchronous ensemble square root filter and a stochastic numerical simulation by means of the Karhunen–Loève expansion of the permeability field. Through this approach, estimation of resin flow behavior for linear numerical experiments is improved and applied to radial injection experiments for the verification of this proposed approach. The results shown the proposed approach is provided accurate estimation of permeability field with low computational cost.
38.	C. Kong et. al.[44]	2016	investigated structural strength of flax/vinyl ester-based composite for the manufacturing of automobile hood using VARTM processing method. In this article, the authors have completed resin flow analysis via polyworx RTM-worx software. According the simulation results, the resin filling time is lesser as compared to resin gel time which simplifies the experimentation.
39.	C. Wang et. al.[45]	2016	determined the flow front pattern and mold filling time using four types of resin injection system for manufacturing of the composite pipe key-part and K/T type joints by VARTM process. The filling time and flow front shape of the experiments shown good agreement with simulation results of FiberSIM. In this study, scale-down composite pipe key part is formed with the optimized resin injection approach to demonstrate the validity of the process and no dry spots observed in cross section view of the cured part. Additionally, actual K/T type joints manufactured with determined and simulated injection process via VARTM. These results also specified the efficiency of optimized injection scheme realized from simulation results.
40.	R. Loudad et. al.[46]	2017	found the approach for simulation of VARTM process as it is complicated. It is observed that there is strong coupling between the resin flow and fiber layup compressibility i.e. hydro-mechanical coupling in account with the coexistence of planar and transverse flows as the contribution of high permeable medium in the process. They have validated proposed model with the aid of multilayer fiber with different materials and orientations including the high permeable medium using experimental approach.
41.	J. Stolz et. al.[47]	2017	used extended physics for modeling of resin flow during vacuum infusion with help of COMSOL multi-physics. They have identified that through coupling of thickness variation and filling process and by integration of a pressure field depending on saturation of preform the flow at a vacuum infusion could be calculated precisely.
42.	S. Ghosh et. al.[48]		In this work, composite specimen fabricated using different carbon fabrics and PETI (two different) resin via VARTM process. Flow simulation has been carried out using LIMS for checking out of plane flow time. It is found that the resin out of plane flow time is significantly shorter than the gel time, which allow large panel fabrication.

Sr. No.	Author	Year	Contribution
43.	F. Fracassi et. al.[49]	2018	proposed the flow model that accounts the effect of resin absorbing nature of fiber due to its inner porosity, affecting the flow. Whereas the traditional theory on VARTM based on Darcy's law, which have restrictions applied to dual scale fiber layup. The final goal is to propose a complete model with the use of dynamic system analysis that saves mold filling simulation time and manufacturing cost. Therefore, in this work, there are two physical phenomena designated by lumped elements: a fluid resistance, which opposes to fluid flow, and a fluid capacitance, which considers the effect of fluid absorption during resin infusion. The flow model has also validated with the experimentation while simulation is completed with a simple algorithm that does not comprise multiple iterations.
44.	M. Hancioglu et. al.[50]	2019	worked on alternate method to illustrate and use of "effective permeability" in the RTM flow model to simulate the VARTM process. The "effective permeability" employed as average in-plane permeability without considering the variation in thickness. There is a deviation found between the experiments and simulations for VARTM with "effective permeability" of 11.1% and 12.3%. hence, it validated the approach.
45.	G. Tuncol et. al.[51]		developed the VARTM simulation model of fiber metal laminate (FML) infiltration process was using the CFD software package FLUENT. They have made 3-D model used the VOF model to monitor the flow patterns along with infusion times, at the top and bottom surfaces of the hybrid perform. The end result of simulation shows well agreement with the measurement obtained during manufacture of FML panel.
46.	Y. T. Jhan et. al.[52]	2011	presented the VARTM experiments on sandwich structure as it is quite complex flow behavior of resin in fiber layers along with segmented core. The authors have defined the porosity of sandwich assembly by using equivalent thickness and projecting equations to simplify permeability calculation. This study also compared with simulation results from 3D model using in plane permeability derived by sandwich assembly porosity. In this article, boat deck infusion experiment has been carried out and compared with simulation results achieved from RTM-worx. The results have shown very close agreement between experimental and simulated flow behavior.
47.	X. Tang et. al.[53]		derived the formula of computation for the fiber permeability and calculated the permeability of the fiber. RTM-worx software is used to simulate tri-body composites boat model for VARTM integral forming process. For the simplification of analysis, model was divided into the upper and lower half. Optimization was carried out using two different mold filling schemes in the form of inlet and outlet ports. The outcome of study shown that scheme two that laying main pipeline along the axis and tubes in a symmetry structure is more reasonable, which can effectively reduce the formation of dry spots as well as the waste of resin.
48.	H. Nakatani et. al. [54]		observed the behavior of resin flow in thick CFRP laminates with corner under VARTM experiment using multiple fiber optic sensors and numerical analysis. It is found that there is delay in resin entrance at the bottom of corner. This was happened due to the collapse and clearance gaps between fabrics at the corner results into decrease in the permeability of distribution medium.

Furthermore, table 2 highlights the direct information on VARTM modeling and simulation such as type of injection strategy, flow modeling method, use of simulation software and its final application by various researchers.

Table 2. Use of VARTM flow methods and simulation software in the research article.

Sr. No.	Author	Flow Modeling	Injection strategy	Flow modeling method	Simulation software	Application
1.	K. Han et. al. [12]	2-D	multiple injection	-----	-----	Boat hull
2.	M. K. Kang et. al. [13]	2-D	Point gate and channel gate injection	CVFEM	-----	Ship hull
3.	X Song et. al. [6]	1-D	Line injection	FE/CV	3DINFIL	Composite flat panel
4.	J. Dai et. al. [2]	1-D	Line injection	FE	RTMSIM	Sandwich Panel
5.	R. Johnson et. al. [14]	1-D	Line injection	-----	-----	Composite panel
6.	R. Chen et. al. [16]	3-D	multiple injection & point injection	CVFEM	-----	Automobile hood
7.	K Hsiao et. al. [17]	1-D	Line injection & point vent	FE/CV	LIMS & GA based simulation software SLIC	co-cured rib structure
8.	A Gokce et. al. [18]	1-D	Line Injection	FE/CV	LIMS	Composite panel
9.	M. Grujicic et. al. [19]	2-D	line injection	CV-FEM	-----	-----
10.	S. Walsh [20]	1-D & 2-D	Line injection & Point injection	FE	-----	-----
11.	A. Khattab [21]	1-D	Line injection	VOF	FLUENT	Composite plate
12.	C. Dong [3]	2-D	Point Injection	CVFEM	-----	flat laminate panel & Cover plate of UAV
13.	C. Dong [22]	2-D	Point Injection	CVFEM		Ship hull & car hood
14.	P. Simacek et. al. [23]	1-D &2-D	Line & center injection	FE/CV	LIMS	Composite plate
15.	J. Lawrence et. al. [24]	1-D	Line injection	FE/CV	LIMS	Glass based composite panel embedded with copper foil
16.	J. Lawrence et. al. [25]	2-D	Multiple injection	FE/CV	LIMS	Upper deck of helicopter pylon assembly

Sr. No.	Author	Flow Modeling	Injection strategy	Flow modeling method	Simulation software	Application
17.	J. Li et. al. [26]	1-D	Line injection	CV & VOF	RTMSim	Flat panels & Boat deck part
18.	C. Dong [27]	1-D	Point Injection	CVFEM	-----	Coverplate of UAV
19.	Y. Song et. al. [28]	2-D	Line injection	FEM	-----	Flat panel
20.	M. Robinson et. al. [29]	-----	Line injection	FE/CV	-----	Composite laminate
21.	Q. Govignon et. al. [31]	1-D	Line injection	FE-CV	SimLCM	Square-hole, dumbbell &dogbone
22.	R. Ranjbar [32]	3-D	Multiple injection	-----	PAM-RTM	Wind-turbine blade
23.	Y. J. Lee et. al. [33]	1-D	Parallel line injection & fishbone pattern injection	FE/CV	RTM-Worx	3-D ship hull
24.	A. George [34]	3-D	Point injection	-----	PAM-RTM	Composite laminate
25.	G. Francucci et. al. [4]	1-D	Line injection	VOF	-----	-----
26.	C Zhao et. al. [36]	2-D	Center to edge, point & line injection	-----	PAM-RTM	Foam sandwich composite plate
27.	W B young[37]	2-D	Point injection	-----	-----	Wind turbine blade
28.	R. Du et. al. [38]	2-D	multiple injection	FE/CV	RTM-worx	Car bumpar
29.	C. Polowick [7]	1-D	line injection	FE/CV	LIMS	components of UAV
30.	C. Kong et. al. [39]	-----	Center to edge, point & line injection	FEM	RTM-worx	Chemical storage tank
31.	B. Yang et. al. [40]	1-D, 2-D & 3-D	Line injection, Center point injection & Two-point injection	VOF	ANSYS Fluent	Flat panel & Automotive hood
32.	C. Kong et. al. [41]	2-D	Central inlet port & outer perimeter channel as exit port	FEM	RTM-worx	Chemical storage tank
33.	G. Struzziero [42]	2-D	multiple injection	FEM	PAM-RTM	Flat panel, L shaped component & T-joint with different thickness

Sr. No.	Author	Flow Modeling	Injection strategy	Flow modeling method	Simulation software	Application
34.	R. Matsuzaki et. al. [43]	3-D	Line & center injection	-----	-----	Composite flat panel
35.	C. Kong et. al. [44]	-----	-----	FECVM	RTM- worx	Automobile hood
36.	C. Wang et. al. [45]	-----	Multiple point Injection	FE/CV	FiberSIM	pipe key part & K/T joints for pipe
37.	R. Loudad et. al. [46]	2-D	Line injection	CVFEM & VOF	-----	Composite plate
38.	J. Stolz et. al. [47]	1-D	Line injection	Level set function	COMSOL Multiphysics	Composite panel
39.	S. Ghosh et. al. [48]	2-D	Point injection	FE/CV	LIMS	Flat laminate panel
40.	F. Fracassi et. al. [49]	1-D	Line Injection	RC-parallel model represented in FE modle	Dynamic System Analysis Tool	Composite panel
41.	M. Hancioglu et. al. [50]	2-D	L-shaped line injection	FE/CV	LIMS	Composite panel with corner
42.	G. Tuncol et. al. [51]	2-D	Point Injection	VOF	GAMBIT, FLUENT & TECPLOT	Fiber-metal laminate panel
43.	Yu-TiJhan et. al. [52]	2-D	fishbone pattern injection	CV-FE	RTM-Worx	boat deck
44.	X. Tang et. al. [53]	2-D	multiple injection	CV/FE	RTM-worx	tri-body boat
45.	H. Nakatani et. al. [54]	-----	Line injection	CV/FEM	-----	composite plate with corner

4. CONCLUSION AND FUTURE SCOPE

An effort has been made to review numerous research articles for VARTM flow model development and its implementation in numerical simulation method. This study enables to determine important process parameters such as the location, number and type of injection gates, permeability of fiber layup, and the permeability and location of the high permeable media for accurate simulation of VARTM. The prime objective of this study was to review and understand effect of flow model, flow modeling techniques and type of simulation tool, helps to manufacture large parts. It was found that many researchers have developed the VARTM flow model which mainly considered the resin flow through the fiber layup and high permeable medium and compaction over the fibrous material. It was also noted that there has been significant amount of research carried out in the advancement of flow model development which are likely to be noted such as effect of number of high permeable medium and its placement, non-iso thermal flow, post filling flow behavior, bleeding of excess resin for achieving high fiber volume fraction, permeability of fiber tows, and resin absorbing nature of fibrous material. Few research articles have been found with the integration of optimization method with simulation tools. It was observed that among the different flow modeling techniques, FE/CV and VOF are most preferable methods. Dynamic permeability characterization of different fiber material and high permeable medium is

highlighted as the important issue in the simulation of VARTM. It has been also noted that computation time for simulation of large part is become crucial condition. Although, there has been few researches indicated for reduction in the computation time through changes in the flow model. There is a lot scope for the enhancement of flow modeling technique which further reduce the computation time. However, even though simulation technique has recognized as an efficient and effective tool in literature, researchers often make assumptions for simplification, which may not be the case in actual situations. Furthermore, the parameters that involve in simulations depend on material structure, environment and other factors, which usually posses certain statistical properties. These variations obstruct the application of the flow simulation.

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