CHAPTER 2
RESEARCH REVIEW

Research review has been performed in seven segments. It is based on history-introduction, natural fibers used in VARTM process, various parameters affecting VARTM process, experimental setup developed, degassing, manufacturing applications and mechanical characterization. The detailed review has been discussed in the following sections.

2.1 HISTORY & INTRODUCTION

The progress of resin infusion under flexible tooling (RIFT) was discussed from the first development of marco method till seemann composites resin infusion manufacture process (SCRIMP) discovered in 1950s. Development of vacuum infusion process was slower (compared to RTM) and generally was lacking in scientific rigour. Research reviewed on VARTM and the potential for scientific development was discussed by Williams (1996). In 1946 the resin infusion was used to manufacture boat hull. Six patterns were developed to describe RTM between 1952 and 1956. During 1980s the use of RTM increased. In development of RTM not much theory was established and the use of RTM was based fully on experimental understanding. This method is one in which scientific theory has come after the actual manufacturing (Potter, 1999).

Bolick (2000) has explained the process of making VARTM laminate, which includes mold preparation, fabric lay-up, sealing the mold, creating a vacuum, resin preparation, degassing, resin impregnation and finally curing of fabricated panels. Kelkar and Tate (2016) have explained the VARTM process for different types of weave pattered glass fabric with use of peristaltic pump and degassing. Thagar (2004) has compared VARTM with RTM, hand layup and forming process with respect to its advantages and limitations.

Summerscales (2005) discussed advantages, limitations, applications and variants of resin infusion under flexible tooling (RIFT). He explained that for each resin there will be dwell time "window" within which high quality laminates could be consistently produced.

Van Oosterom et al. (2019) compared six different resin infusion methods VARTM, SCRIMP, CAPRI, DBVI, VAP, and PI with respect to amount of resin supply, fiber volume fraction, void content, short beam strength and compression strength. It was found that the laminates were having major difference in properties except void content due to variation in infusion methods. Arne Hindersmann (2019) has reviewed almost all the variants of VARTM process.

Raju and Vinay Rao (2014) worked on benefits of the composites lab to the academia/research to bridge the gap between industry and academia in the composites context. Three types of labs: basic, intermediate and advanced were discussed along with market study of India's position in the world composites industry.

Classification of LCM in three categories: RTM, VARTM and VARI depending on resin supply system was discussed by Schledjewski and Grössing (2016). The paper discussed advantages and limitations of vacuum infusion vs. RTM.

2.2 NATURAL FIBERS

Since 1990s research has focused on natural fibers. The growth of natural fiber will generate employment in India. The renewed interest in the natural fibers is due to their lightweight, low density, nonabrasive, non-irritating, combustible, nontoxic, biodegradable, eco-friendly, good sound absorption capacity, less processing time, wood like appearance, low energy consumption, zero CO_2 emissions if burned, low cost, easy availability and renewability as compared to synthetic fibers, has resulted in a large number of applications to bring it at par and even be considered superior to synthetic fibers. However the limitations are temperature resistance, maximum up to 150-200 °C, high moisture absorption and low strength as compared to man-made fibers.

Various chemical treatments are available to improve the quality of natural fibers. Generally fibers contain cellulose 60-80%, hemicellulose responsible for 20% moisture, pectin, and 5–20% lignin (Saheb and Jog, 1999) and (Cristaldi *et al.*, 2010).

The book written by Ho *et al.* (2012) provides information about various natural fibers, their properties, treatment required, weave patterns, the construction of fibers and cost application. It includes classification of natural fibers and resins. It discusses various methods of manufacturing composite with natural fibers which includes LCM for large structure. Begum and Islam (2013) reviewed that natural fibers are popular but cannot replace the synthetic fibers in certain application where mechanical strength is important.

Xia et al. (2015) used Kenaf fibers to manufacture laminates with untreated polyester resin. In comparison of hot compaction and VARTM they found that VARTM give more advantage in terms of lesser manufacturing cost, increased volatile organic compound and high tensile and bending strength.

Salman et al. (2015) studied physical, mechanical and morphological properties of composites from plain woven Kenaf fabric with three different thermoset resins, i.e. epoxy, polyester and vinyle ester using a vacuum infusion technique. They found that the composite at 0°/90° fiber orientation gives better tensile strength, flexural strength and tensile modulus than at +45°/-45°.

Lagardère et al.(2014) explained the effect of mass sink and source in natural flax fiber during VARTM process and they redefined Darcy's law equation by adding that flow rate is dependent on mass sink and mass source effect. They proposed a new resin flow model in the natural fiber reinforcement considering two particular features a) permeability change because of fiber swell b) mass sink and source effect owing to the liquid absorption and fiber swell.

Sanjay et al. (2016) provided details about the potential use of natural fibers and its composite materials, mechanical and physical properties and some of their applications in engineering sectors. Sanjay et al. (2018) has reviewed papers on various manufacturing techniques used for natural fibers and has consolidated tables on results of various mechanical characterization for natural fibers.

Bodaghi et al. (2019) reviewed variation in permeability due to fiber architecture like tow waviness, tow size and shape, handling, storage, damage during lay-up, due to drapability, due to nesting. Dual scale permeability in natural fiber is more complex as within and between tow permeability has to be considered. Permeability error can be due to measurement error or micro variation which cannot be observed by naked eyes. This will lead to a thicker part and more scrap.

Table 2.1 demonstrates review of natural fiber with type of resin, fiber volume fraction (FVF) achieved and mechanical testing performed.

Table 2.1 Natural fiber volume fraction (FVF) comparisons

Sr No	Natural Fiber +Resin	FVF	Tests Performed	Manufacturing Method	Reference
1	Jute + Polyester	60 %	Tensile, ILSS (ASTM 2344), Charpy Impact	Hand Layup	Roe and Ansell (1985)
2	Jute/ Bamboo + Polyester / epoxy	60% 85%	--	--	Saheb & Jog (1999)
3	Recycled paper/ Flax mat Cellulose + Soya oil	42.3% 31 %	DMA Test (ASTM D50230), Flexural Test (ASTM D790-93)	VARTM	O'Donnell, et al. (2000)
4	Hemp /Flex/ Kenaf + Vinyl ester	12 % 10 % 9 %	Tensile test (EN ISO 527)	Hand layup	Cristaldi et al. (2010)
5	Jute + Polyester	24%, 30%. 37% 42%,	-----	Compression cycle	Francucci et al. (2012)
6	Remin + Epoxy	12-30%	Fiber mass fraction, Tensile, Flexural, ILSS, Fiber tensile	VARI, Hot compression cycle	Gu et al. (2014)
7	Flax + Vinyl ester	51 %	Tensile, Compression, Flexural	VARTM	Kong et al. (2014)

2.3 PARAMETERS AFFECTING VARTM PROCESS

Consolidated research review has been performed on various parameters affecting VARTM process. Table 2.2 highlights review on material, various parameters affecting VARTM process, testing/ measurement performed and kind of instrument used for various VARTM experimental setups.

Table 2.2 Research review on process parameters

Research	Material	Processing Method	Control Parameter	Testing and measurement	Instruments Used
Gama et al. (2001)	Plain weave glass and epoxy	VARTM	Debulking cycle, Flow rate control by open-open, close-open, close micro open	Thickness variation, FVF, Flexural stress	Laser displacement meter, Lab view s/w
Sharma and Siginer (2009)	UD glass, BD glass, UD carbon	SCRIMP	Types of fabric (E glass UD, BD and Carbon BD, hybrid), Resin pressure (0, 10 , 20 psi), Vacuum pressure (27,28,29 in Hg) Debulking (applying pressure after closing inlet)	FVF, Void content, Tensile strength and Tensile modulus, Thickness gradient	-
Grimsley et al. (2001)	Carbon Fabric + Epoxy	VARTM	Flow front	Resin Pressure, FVF, Panel thickness	Camera, pressure sensors, LVDT, Lab view S/w
Li et al.(2004)	E glass + Epoxy	VAP and SCRIMP	Membrane	Thickness variation, Void content, FVF, Short beam shear test	SMART Weave sensors, CCD camera, glass tool.
Naik et al. (2014)	-	RTM / VARTM	Architecture (weave style, surface condition, porosity), Mold design, part geometry, Human factor, Resin properties (viscosity, surface tension, contact angle), processing condition (injection pressure, flow rate, temperature)	Flow velocity, 1D, 2D, 3D permeability	Camera, Flow Sensors

Bender et al. (2006)	Corn syrup and water	VARTM	Flow rate	-	Fuzzy logic controller, lab view, Precision Weighting Balances, Pressure controller, Viscometer
Yoon et al. (2005)	Two different fabric + Corn syrup with water mixture with density approx. epoxy	VARTM	Gravity effect (horizontal, upward, down ward), Tube diameter and tube length	Flow, Resin fill time	Time-domain reflectometry (TDR) sensor, Pressure, Five pressure transducers, Viscometer
Govignon et al. (2008)	E-glass fabric with different GSM + Mobil DTE AA resin and Mobil DTE Heavy resin	Resin Infusion (RI)	GSM of fabric(480 g/m2, 800 g/m2 Biaxial stitched matrix), With and without HPM, Fluid viscosity	Thickness variation during filling and post filling, Resin flow rate, Flow velocity, Filling time, Resin pressure, FVF, Permeability	Thermocouple, Pressure transducer, Two high resolution camera for stereo photography, Weighing scale, 20 cm wide strip
Yenilmezet al. (2009)	Fabric (Fibroteks) Resin (Poliya PolipolTM 336-RTM)	Vacuum infusion (VI)	Dry compaction Cycle	Thickness and pressure variation during flow	Digital dial gauge, Pressure transduces
Francucci et al. (2010)	Jute/ Glass fabric, 22% V/V water/glycerin solution	VARTM	Viscosity of resin, Porosity, Type of fabric	Saturated and unsaturated permeability, Swelling of fiber	Viscometer Vacumometer, Optical microscopy

Rigas et al. (2001)	Glass fabric and epoxy	VARTM	HPM, Height of resin supply to find effect of gravity, Single and double vacuum bagging	Resin flow, Variation in part thickness, FVF, ILLS, Flexural test, Tensile, ILSS, Infusion time	SARTM Weave sensors
Ghabezi et al. (2010)		VARTM	Tube diameter, Length of tube	Filling time, Pressure drop	-
Kedari (2011)	Chopped Glassed mat + Polyester	Heated dual Pressure control VARTM	Inlet pressure, Outlet pressure, Mold temperature,	Composite density, FVF, Hardness, Effect of Degassing, Viscosity of resin	Digital heater, resin trap to control vacuum and resin pressure they used pressure reservoir
Arulappan et al. (2014)	Carbon fabric + Epoxy	VARTM	Fiber orientation, Configuration gravity, HPM	Pressure, Thickness variation, Filling time	Pressure sensors, LVDT
Nasir et al. (2015)	GFRP + KFRP	VARTM	Laminate with different material	Tensile strength, Tensile modulus, Opening displacement curve	Fixture was made to make tensile coupon
Chokka et al. (2019)	Carbon + Epoxy	Vacuum infusion (VI) + Hand lay up (HL)	Viscosity (SA + NSA), Vacuum pressure (50,250,350,500 mm of Hg)	Tensile , Wear properties, FVF	-

Chang and Chen (2016)		VARTM – progressive compression	Vacuum pressure (100, 80 KPa) Number of compression segment (2, 3) Compression timing of the next segment (5. 10 sec) Temperature of the heated air (20, 40 °C) Initiating segment of the heated air ($1^{st,}$ 3^{rd}) Initial cavity height (7, 10 mm) volume of infused resin (100, 130 ml)	Filling time	Taguchi method
Das et al. (2016)	Plain weave jute + Polyester	Hand layup and compression at 90° C for 10 min	Staking sequence	Tensile strength (TS), Tensile modulus (TM), Bending strength (BS), Bending modulus (BM), and Impact strength (IS)	-
Wang et al. (2016)	Carbon fabric + Epoxy + Edible oil	VARTM	Compaction pressure, Number of layers, Liquid viscosity, Post filling time	In plane permeability, Preform thickness	Vacuum pressure control, Eddy current sensors

Pishvar et al. (2018)	Random mat - E glass + Epoxy	Magnet Assisted Composite Manufacturing (MACM), Wet lay-up vacuum bag (WLVB), VARTM	Magnetic compaction	FVF by LOI, Density, Flexural properties, SEM, Thickness variation	-
Yalcinkaya et al.(2017)	E glass fabric + Epoxy	Pressurized and heated VARTM	External pressure at given time for compaction, Mold temperature, Degassing	FVF, Flexural strength, Void content	Heat sheet insulated with silica fabric, electrical scale, solenoid valve and pressure regulator, Lab view
Yalcinkaya et al. (2018)	Glass + Epoxy	Pressurized Infusion (PI)	Inlet pressure (0,90,180 Kpa) Chamber pressure (0,100,200 Kpa), Without and with bleeding	FVF, Fill time, Void content, Short Beam Strength	Flatbed scanner, Gauges
Yalcinkaya et al. (2019)	Glass + Epoxy	Pressurized Infusion (PI)	External pressure (0, 34.5, 69, 138 KPa), Resin flushing, Number of ply (6,12,18)	Void content, FVF, Flexural properties, Short bean shear strength	Gas pycnometer, Micrometer to measure thickness, Digital image analysis for void content
Nauheimer et al. (2017)	Glass fabric + Epoxy	VARTM	Pressure drop	Flow front	Pressure sensors
Sunilpete and Cadambi (2020)	Glass fabric + Epoxy	Vacuum infusion (VI)	Double bag, Resin trap, Silicon bag	Density test, FVF, void content, DMA, Tensile, Flexural, and ILSS.	-

2.4 VARTM EXPERIMENTAL SETUP

Different types of VARTM experimental setups have been developed by different authors. Heider et.al. (1999) have established VARTM setup and studied the effect of vacuum to control the resin flow. To ensure that the setup is satisfactory, they change the input pressure and observed the variation in reading by vacuum and pressure sensors. They observed the bigger diameter tube generates more vacuum than the smaller one. They performed a special experiment, where in, injection was conducted in two stages. The schematic diagram is shown in Figure 2.1.

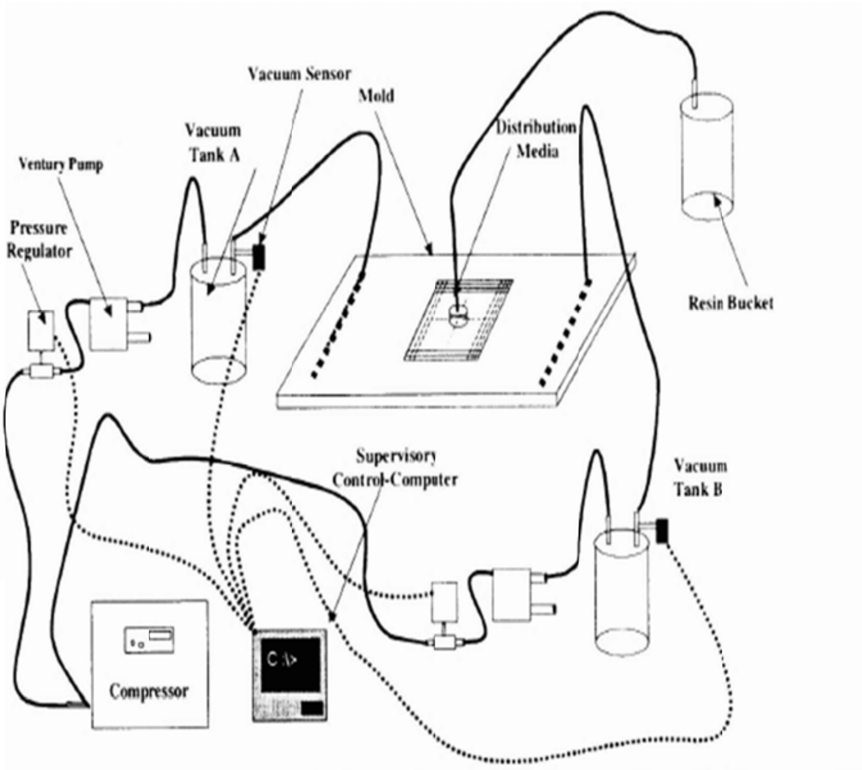

Figure 2.1. Schematic of VARTM Control system incorporating computer control pressure and vacuum in-situ vacuum sensing for two individual vents. (Heider et.al., 1999)

In the first stage, vents on two opposite sides were controlled to low and high vacuum with the described vacuum system. The low-vacuum side was fixed to 10 inHg, whereas the high vacuum side was set to 23 inHg. In second stage when the resin arrived at the high vacuum vent, the vent was turned off and the low-vacuum vent was transferred to high vacuum at a level of 25 inHg. The complete control system was turned off, once the resin reached the second vent. The VARTM injection was done from the centre and the flow pattern was completely dragged towards one side of the composite part. Thereafter, the controlled process was reversed and compete filling of resin in laminate was done. The process was controlled by sensors, fuzzy logic based computer controlled pressure regulators and venturi pumps.

Ronnie (2000) explained the procedure required to perform VARTM process. As per this paper, the leak check should be done after applying 2 Torr vacuum and then shut off vacuum supply, observe the system for 30 minutes and allowable leak should not be more than 0.5 Torr. The special peristaltic pump for resin impregnation was used which works with very slow rpm with 70% on and 30% off timer. The laminates were cured inside the mold for 24 hours at room temperature after impregnation.

The experiment was repeated by Kelkar and Tate (2002). They followed the same method and used different woven and braided fabric and conducted the test to find fiber volume fraction. They used Ignition method, areal weight method and density method to find fiber volume fraction for three different materials. They found that the average weight volume of fiber for all three cases were around 50%.

Grimsley et al. (2001) has worked on VARTM experimental setup to study resin pressure and thickness variation during actual infiltration process. The resin degassing was done at room temperature for 1 hour for full vacuum. The component was post cured at 177°C for 6 hrs. The dry and wet fabric compaction was measured and was found 53% and 58% respectively. These show that the lubrication compacts of the fibers and increase fiber volume fraction. Study was also done to find the effect on flow rate with increase stalking and viscosity of resin. Dry compaction with loading, wet compaction and wet unloading with spring back effect were observed during the experiment.

Rowe et at. (2005) studied fill front and cure progress monitoring with experimental setup. The experimental setup included sensors, signal conditioning, DAC and signal post processing components. FEF (Fringing Electric Field) Sensors were used because they were sensitive to small variation. They were used to monitor resin position during impregnation and curing. Only single side contact of material was required as they were transparent to monitor the resin flow front.

Control of flow rate during filling with fuzzy logy controller with sensors was done by Bender et al. (2005). The flow position was detected via sensors and resin was weighed from infusion bucket. The error in terms of change in pressure required was calculated with respect to desired flow position and resin weight in bucket. The error is fed to fuzzy logy controller which will decide the change in pressure required; accordingly the pressure regulator will control the flow rate. It was noted that, initially the pressure difference between inlet and outlet will be high and hence one should keep initial resin pressure low. Gradually during flow, the pressure bas to be increased to keep flow rate constant. The system has been implemented in LabVIEW and allows feedback from both sensors as well as virtual simulation results.

El-Chiti et al. (2006) developed 3-D digital image correlation system to monitor full field during tensile, compressive and shear test coupon for VARTM process. This system solved the issues which are faced by conventional direct contact measuring instruments, like strain gauge and LVDT, which includes limited single point contact, time consuming, misalignment issues, removal of instrument during testing to avoid damage, surface contact requirement and transverse sensitivity. The advancement of high resolution camera reduces the variability in material testing and provides mature, efficient and high performance testing.

As shown in Figure 2.2., an experimental set up was developed to check the variation in part thickness during and after injection with laser technology scanner by Lawrence et al. (2007). The author has confirmed that the part thickness reduces initially during infusion due to lubrication effect and then gradually increases due to fluid pressure. However the part thickness further increases after infusion due to the inside pressure built up with resin flow. It is noted that the resin viscosity plays an important role, because as the viscosity increases; proper compaction pressure is required to control the part thickness. For comparing viscosity with compaction load author has used oil and water and applied pressure with solid and perforated pressure plate.

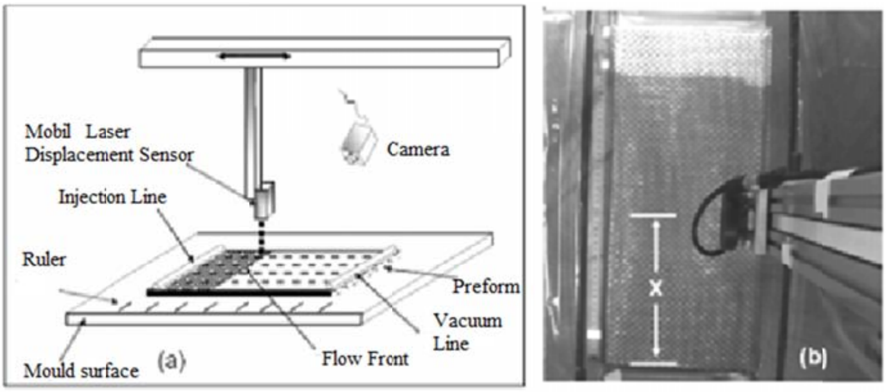

Figure 2.2 a) The Schematic of the laser scanner to increase during infusion b) the laser scanner above the mold. (Lawrence et al., 2007)

Important learning from the paper written by Tackitt and Walsh (2007) includes, it is possible to achieve FVF up to 50 – 55% with VARTM process. As the fluid impregnates inside the fabric, over a period of time displacement reduces and pressure gradient also reduces. The flow takes place due to change in pressure and the fiber lubrication induces compaction in laminate which finally results in increase of fiber volume fraction. As the flow rate reduces, full penetration is achievable and more compact laminate is possible. The point source is better option than line source. As the fabric compacts during dry stage, the thickness reduces, permeability reduces and more pressure is required to inject the resin. The thickness of laminate will be more at resin inlet than outlet.

Kuentzer et al. (2007), worked on how to control the void distribution during VARTM. The void can be macro void between the tow and micro void inside the tow. They performed four experiments. In first experiment normal VARTM process was adopted, in second they introduced bleeding of resin, i.e. resin flow time twice than normal, in third they provided resistance at the out let by reducing vent pipe size 1/3 and finally in fourth experiment combining both the technique of bleeding and applying resistance at outlet. The authors have found that void content was least in fourth case.

Goren et al. (2008) has developed VARTM experimental setup by controlling the temperature and vacuum during and after curing with PLC system. The temperature is controled up to 200°C with PLC and temperature control screen. The vacuum is controlled manually with vacuum control valve. With this, high quality and void free composite can be fabricated.

Yenilmez et al.(2009) worked on variation in part thickness and compaction pressure during vacuum infusion process. Two sets of experiments were performed which include fabric characterization experiment and actual VI Injection. The results were compared with Correia model. They found that final part thickness depends on, initial vacuum duration, geletion time, resin pressure and shrinkage ratio of resin system. To reduce the variation in part thickness, one should properly plan the locations of injection and vent holes.

The full VARTM experimental set up has been demonstrated by Plunkett (2010). Lab view software had been used to observe resin flow rate. The pre checks before impregnation has been mentioned. How to use Labview software during execution of the process with camera system for use of proper illumination of light to capture image during impregnation has been explained. The post processing activities required after impregnation has also been discussed.

Larimore (2012) experiments have been done to use bladder bag reservoir to apply fixed amount of resin during laminate making for glass fiber and epoxy resin. The bleeding of resin was not uniform during experiment from the bladder bag and special initiation device was manufactured to tear the bag. The amount of resin for bladder bag was calculated depending on volume fraction required by laminated plate theory. They made six laminate with FVF (30- 60 %) and they found that FVF with 55% had minimum void content.

Anderson et al. (2013), worked on high pressure VARTM system to improve fiber volume fraction, tensile strength and modulus compared to normal VARTM process. The VARTM was used. Before curing, bladder plate was used to apply pressure of 0, 69, 207, 345 and 438 kPa with three different plies of 6, 12 and 18 layers. With HP-VARTM, the fiber volume 29%, tensile module 25% and tensile strength 24% was increased then the laminate was produced with conventional VARTM process.

Ricciardi et al. (2014) introduced pulse infusion process with static and dynamic mode. Four experiments were performed which includes Vacuum Infusion Process

(VIP), Double Bladder VARTM (DBVARTM), Static Pulse infusion(SPI) and Dynamic Pulse infusion (DPI) process. They analyzed composite laminates made by DPI process with respect to mechanical testing, density, void, and morphological analysis. Authors concluded that DPI is a better technique and cost efficient technique due to absence of distribution media and less use of resin.

Yokozeki et al. (2014) as shown in Figure 2.3, worked on porous mold process (PMP) and tried to control the property during VARTM process. They introduced the concept of thickness change ratio. They first established the equation for variation in thickness change with respect to resin input for CFRP with the help of a laser sensor, and after that they controlled the input resin supply and calculated thickness change based on thickness change ratio for given numbers of ply, which was experimentally proven effective. They have also concluded that as number of layer increases the thickness change variation also increases.

Figure 2.3 Top view of resin infusion behaviour. (Yokozeki et al., 2014)

A novel device, as depicted in Figure 2.4 was developed by Changchun et al. (2015). The pressure sensors, aluminium platform, thickness test module and pressure test module were connected with computer. It was used to measure in plane permeability and through thickness permeability of composite laminate. The permeability was checked by three methods; with camera, FBG sensors and a novel device. All the devices gave almost the same result. In plane permeability was greater than through thickness permeability. It was observed that as number of layers increased in plane permeability increased.

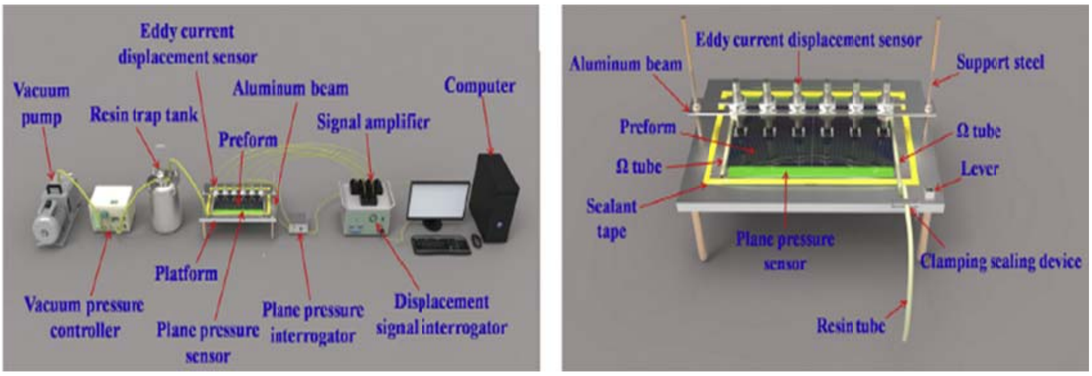

Figure 2.4 Schematic diagram of an integrated experimental setup for testing in-plane permeability adopted in the study. (Changchun et al., 2015)

Wang et al. (2016) has worked on the same setup and developed another paper which concluded that as the viscosity increases flow rate increases. The through thickness permeability was less than in plane permeability. The thickness of fabric was highest at inlet and reduced at the outlet. During post curing, the thickness reduced and fiber volume fraction increased. In dry compaction laminate thickness reduced less than in wet compaction laminate.

Arulappan et al. (2015) has done a very good review on development of VARTM with experimental setup till 2014. In the paper authors have varied three parameters, viz., (i) test configuration (flat plate, plate with hole, L-section); (ii) layup of UD-preform (0/90 and quasi); and (iii) HPM (with and without). For each configuration, three trials were conducted. Total 42 infusion tests were carried out. For each infusion, compaction pressure and thickness variation during resin infusion were observed. They observed many important points like infusion time reduces drastically with the use of HPM. Steady state reached in case of flat plate was faster when compared to plate with hole. The gravitational effect in the flow was studied, and it was observed that thickness gradient was smaller in vertical than in horizontal laminate.

Poorzeinolabedin and Parnas (2019) used electro magnetically induced preform resting (EIPR) to dynamically control the resin flow by providing electromagnetic vibration to the flexible part of mold and reduced dry spot for VARTM process.

Gajjar et al. (2020) prepared CFRP laminates with three different thickness 4, 8 and 12 mm. Thickness variation, warpage, volume fraction and pressure were measured along the length of laminate during impregnation. The pressure was measured with pressure gauge and thickness variation with 3D non-contact scanning technique. The experimental setup arrangement is shown in Figure 2.5.

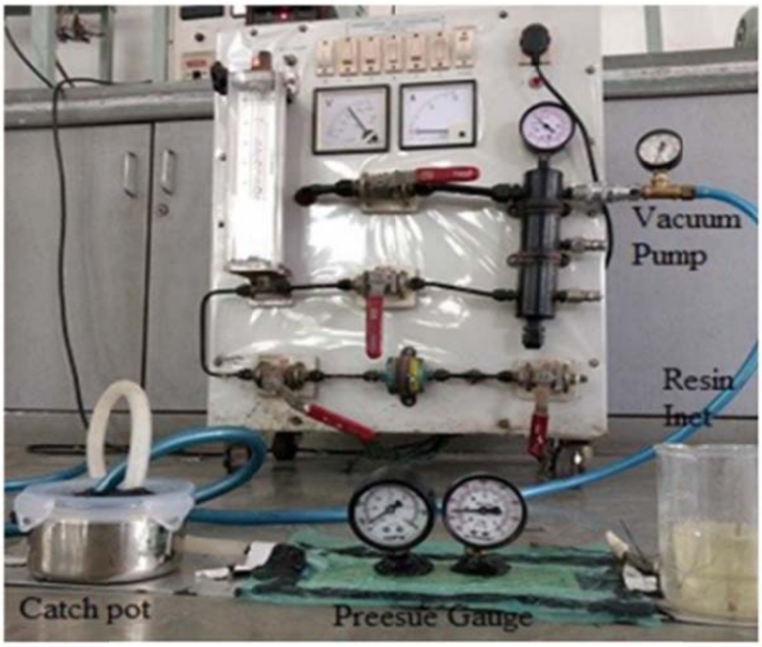

Figure 2.5 Actual experimental setup for the vacuum infusion process.(Gajjar et al., 2020)

2.5 EFFECT OF DEGASSING

Degassing is necessary to remove air entrapped inside the resin before actual impregnation. Bolick (2000) explained that well degassed resin reduces air pockets. Brouwer et al. (2003) said that degassing reduced the risk of entrapped gas during the flow and increased capabilities to dissolve the bubbles in the resin. The reasons for void could be reinforcement permeability, dissolved gases in resin, shrinkage of resin and leakage at sealant tape. According to him the standard method to degas the resin was by applying vacuum. Bubbles would only come if bubbles or bubble nuclei were present in resin. When the pressure was reduced the bubbles would increase in size as per gas law and with increase in size the rising speed of bubbles would also increase as per Archimedes law. Henry's law states that “gas solubility decreases as pressure reduces”.

Govignon et al. (2011) worked on controlling the part quality in the vacuum infusion process. Void content was measured microscopically. Li et al. (2004) concluded that the void is generated due to entrapped air during infusion, leakage in vacuum bag, staging of resin, entrapped air in fiber bundle or curing. They suggested good practices such as vacuum de-bulking, degassing, location of vent at the end of fill and optimizing resin cure. Prasad (2004) performed degassing by keeping resin at room temperature in vacuum chamber at high vacuum for an hour and again heating at 65° C for 30 minutes to reduce viscosity.

To make the resin bubble free during infusion Afendi et al. (2005) suggested various degassing methods like normal degassing, bubble nucleation agent method and air spray method. They suggested that increasing void by 1%, reduces the ILSS strength by 7%, flexural strength by 10% and the flexural modulus by 5%. They explained that the gas dissolved by 1.7% would expand 50% by increasing vacuum 20 mbar. The reason for void formation was either due to entrapped gasses, volatile material, temperature rise, resin shrinkage, leakage of sealant tape or boiling of volatile components. The degassing was performed at 90 mbar for 15 minutes. Degassing got over when bubbles stopped coming out of resin. If it occurred at initial stage, degassing wasn't required. The micro bubble (diameter less than 500 μm) still remained in resin after degassing. Heating could improve degassing process but reduced pot life and hence heating could be used only to a certain limit.

Ghose et al. (2009) modified the thermal cycle to reduce void content from 7% to 3%. The authors concluded that doing degassing for optimum time was important but over use of degassing would not enhance void content. Kedari et al.(2011) suggested that high temperature and vacuum with low impregnated resin pressure would generate part with low void and high volume fraction. They performed degassing at 0.336 bar for 15 minutes at room temperature. They said that void formation may depend upon vacuum pressure, mold temperature, flow pattern, porous size and dual scale flow behaviour media. To minimize entrapped voids they advised to apply vacuum during impregnation, degassing of liquid before impregnation, allowing the resin to flow freely in mold to carry air bubble at vent and double vacuum bagging. Amirkhosravi et al.(2018) could achieve reduction in void content within 1 % using stationary and movable magnets for dry compaction. Yalcinkaya et al. (2019) could achieve reduction in void content up to 1% by applying 138 Pa gauge pressure on vacuum bag for high temperature VARTM process.

Park and Lee (2011) studied modelling of void formation and concluded that void was formed due to heterogeneous nature of fabric, mechanical air entrapment, nucleation, leakage, cavitation, uneven resin curing etc. They talked in detail about micro and macro bubble generated within and between tow. They called them as tow void and channel void. Generally resin velocity of 0.1-1 mm/s was considered to obtain optimum capillary number of 10-3. This value ensured that there was minimum void formation during flow. Capillary number was defined as ratio of capillary force to hydro dynamic force.

Dewan et al. (2013) used jute and polyester resin and performed degassing of resin before and after mixing it with MEKP and cobalt. They calculated void content as per ASTM D273-9M. Yalcinkaya et al. (2017) confirmed that degassing was important before curing and hence they also performed degassing of resin for 2 hours for epoxy and hardener mixture. Grimsley et al. (2001) performed degassing on epoxy resin for one hour in full vacuum at room temperature.

From the above review it is clear that degassing definitely helps to reduce void content and also improves the strength of laminate. How much degassing is to be done depends on how much air is entrapped inside the resin. It is to be noted that degassing without entrapped air inside the resin has no meaning.

2.6 MANUFACTURING

Brouwer et al. (2003) wrote a paper on vacuum injection molding for large structural application. They described ways to improve reliability and predictability of the VARTM technology in order to decrease development cost and to reduce the risk of failures during production. It showed ways to achieve void free composite and injection strategy to optimize composite properties in large structure.

Takeda et al.(2005) examined ways to improve existing VARTM techniques so that they can be applied to the fabrication of aircraft primary structures and to improve VARTM materials, processes, and cost. Vertical stabilizer of MJ aircraft was fabricated by VARTM process. In this process hot compaction of the base material prior to resin infusion, bleeding of excess resin after resin infusion and other steps were taken to get higher FVF. Special non crimp woven fabric with improved unidirectional properties and two component epoxy resin system with low viscosity, which was superior in infusion into preform were developed. Resin distribution media was used and excess resin was bled off from resin port. It was verified that the strength and elastic modulus properties were acceptable for empennage i.e. tail assembly. The part quality was equivalent or higher than prepreg process and had less production cost. Fiber with superior drapability, defects like resin rich, resin starvation and wrinkle were not observed.

Kamae et al. (2009) worked on material technology to build aircraft structures with advanced VARTM method (A-VARTM). They developed new material technology in which a toughened low viscosity epoxy resin system and a non-crimp woven fabric was used and they got excellent mechanical properties and no micro cracks after thermal cycles. They also observe the morphology with Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) and concluded that resin is well mixed with reinforcement.

Anderson et al. (2013) used inflatable bladder i.e. compressor plate to make laminate with VARTM process. In this work, a variation of VARTM technique is introduced which utilizes a pressurized flexible bladder to apply a consolidated pressure in addition to that of the ambient pressure on a preform immediately after it has been impregnated. Experiments were performed with different layers of glass fabric with epoxy and with different bladder pressure. They observed that fiber volume fraction, tensile module and tensile strength increased 29%, 25% and 24% respectively with use of inflatable bladder HP-VARTM process than conventional VARTM process. They concluded that volume fraction does not increase by increasing numbers of ply. They also observed that by increasing bladder pressure fiber volume fraction increases up to certain limit but further increasing the bladder pressure, there is no significant change. They also observed by increasing bladder pressure there is reduction in laminate thickness.

Riccciardi et al. (2013) introduced new cost-saving vacuum infusion process called pulse infusion. In this process two vacuum bags were taken and the resin distribution net was eliminated. The lower vacuum bag determines a lower chamber where the resin infusion occurs most likely in the VARTM. On the lower vacuum bag a properly designed pressure distributor was positioned on which second vacuum bag was placed which was identified as upper chamber. By applying a different vacuum pressure in the two chambers and controlling the pressure difference between the two chambers timely, the resin flow was pulsed and promoted both in the plane and through the thickness of the reinforcement by either static or dynamic mode. It was observed that the fiber volume fraction and tensile strength results were similar to that of VARTM process, however, flexural strength and modulus was 24% and 9% more than normal process. It was also found that 19% reduction in cost was possible with this process compared to vacuum infusion process (VIP).

Verma et al. (2014) furnished a paper on processing of a co-cured wing test box of aircraft structures using vacuum enhanced resin infusion technology (VERITy). The objective was to realize a co-infused and co-cured wing test box consisting of bottom skin, spars, ribs, gussets and stringers. Infusion of resin into well compacted network of reinforcement with varying thickness was tricky and difficult because of complex flow characteristics. Both parallel and series infusion were adopted. In this process building block approach was adopted to develop the final product. Risk mitigation was done through testing at coupon level, element or detail level, and sub component level and finally at component level. A systematic approach was adopted wherein rheological studies were carried out using dielectric method to determine the pressure application window (PAW). A-Scan and C-Scan, mechanical testing, structural testing were done to test the part at different manufacturing stages. Resin infusion strategies were decided based on tool design, like more number of resin ports were given at thicker areas, facility for heating and degassing the resin and provision for PAW was available.

Poorzeinolabedin et al. (2014) made a numerical model where they did number of simulation with various gate and vent boundary location to determine the optimum filling process by PAM_RTM software for car body part.

Ma et al. (2014) worked on co-curing of prepreg and resin film infusion for I-shaped stiffened skin for epoxy resin with four different kind of carbon fiber prepreg.

Autoclave curing was used and resin flow front and resin pressure were detected by self-developed monitoring system. Optical micrographs testing and thickness measurement were employed to evaluate processing quality. The result showed good mechanical properties at interface region. It was concluded that CO-RFI process is a promising method to fabricate composite structure with high flexibility in materials and structures.

Gajjar et al. (2019) published a paper on cured reflectors manufactured using autoclave and VARTM manufacturing techniques. Dimensions were measured to compare two techniques and it was found that the percentage difference was within the acceptable limit.

Maung et al. (2020) used Vacuum Assisted Resin Infusion molding process to simulate fuselage skin and analyzed requirement of number of port and amount of resin required. Fluent software was used for analysis.

2.7 MECHANICAL CHARACTERIZATION

Chiti et al. (2006) developed 3-D digital image correlation system to monitor full field during tensile, compressive and shear test coupon for VARTM process. This system would solve the issues which are faced by conventional direct contact measuring instruments, like strain gauge and LVDT, which includes limited single point contact, time, misalignment issues, removal of instrument during testing to avoid damage, surface contact requirement and transverse sensitivity. The advancement of high resolution camera will reduce the variability in material testing and will provide mature, efficient and high performance design.

Kelkar et al. (2006) conducted performance evaluation of VARTM manufactured textile composites for aerospace and defence applications. The basic objective were a) to compare tension-compression fatigue performance of twill woven S2 glass/vinyl ester and plain-woven S2 glass/epoxy integrated armored vehicles and b) to perform and compare low velocity impact performance of stitch-bonded E glass/vinyl ester and woven roving E glass/vinyl ester composites for naval application. It was concluded that fatigue life of plain-woven S2 glass is better than twill woven S2 glass and the stitched bonded displayed better impact resistance properties than woven roving.

Vakuzadeh et al. (2012) compared vacuum bagging (VB) and VARTM by comparing physical and mechanical behavior of composite laminate, with stitched biaxial E-glass fiber reinforced with epoxy resin. They concluded VARTM process leads to higher tensile strength (21%), tensile modulus (10%), flexural properties (16%), density (5%) and volume fraction (15%) compared to VB. They used ASTM D3039 for tensile test, ASTM D790 for flexural test and ASTM D792 for density and FVF check.

Jweeg et al. (2012) worked on theoretical and experimental study of mechanical properties for different types of reinforcement fibers in composites. In theory, equation for mechanical characteristics of unidirectional ply, woven fabric, mats, spherical (powder) fillers, discontinuous (short) fiber- continuous (short) fiber, randomly oriented discontinuous fiber are derived. Mechanical properties were also found with the experimental study of composite materials, which includes study of different types of composite materials with various volume fractions of reinforcement fiber such as powder, particle, long, woven, and short reinforcement glass fibers. They tested density, tensile, modulus and FVF for different resin matrix (epoxy, polyester, nylon) and fiber reinforcement (Glass, Carbon-HS, boron) composites. The main conclusion of this work is (i) Best modulus of elasticity for composite materials were, for unidirectional composite materials in longitudinal direction and for woven composite materials in any direction. (ii) The powder, particle, mats, and short fiber composite materials may give isotropic properties of composite materials which depend on resin materials properties.(iii) The variables of matrix materials affects the properties in powder, short, and mats composite materials more than in properties of woven and unidirectional composite materials. (iv) Unidirectional composite materials give minimum modulus of elasticity in transverse direction compared to other composite material types. (v) As mechanical properties of reinforcement fiber increases, properties of composite materials also increase.

2.8 FINDINGS

Though the use of the VARTM process started after 1940s for structural application, the demand for more sophisticated VARTM had arisen after 1990s, when it was envisaged to apply this technology to meet stringent requirement of airframe and defense applications.

There are different variants of VARTM such as A-VARTM, CAPRI, SCRIMP, VERITy, VARI, RIFT, PI etc. Large products can only be manufactured cost effectively by using a vacuum injection technique. Basic theory of VARTM starts with Darcy's law. Initially it was used to find permeability in incompressible porous media with RTM process. A further analytical formulation has been developed to find permeability in compressible porous media for VARTM process.

Significant study of research review has been done till date to find out the effect of different parameters affecting VARTM process. The findings are tabulated in the form of parameters which can be controlled or measured during various stages of experiments (Refer Table 3). The fish bone diagram for various parameters affecting VARTM process is shown in Figure 2.6.

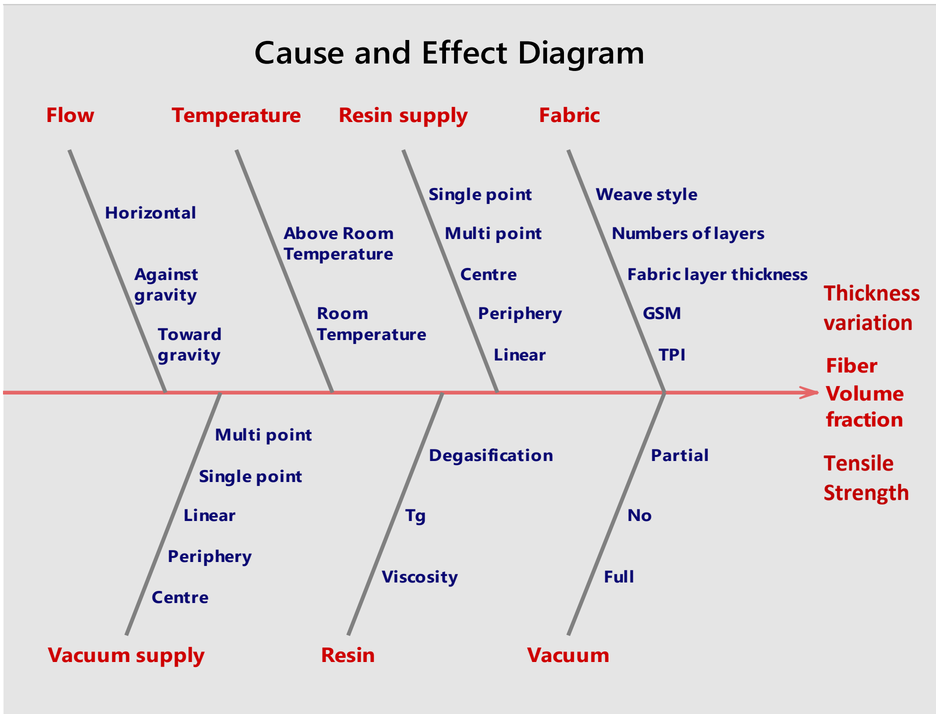

Figure 2.6 Cause and Effect diagram for parameters affecting VARTM process

Table 2.3 Parameters affecting VARTM process

Control Parameters		Measured Parameters	
Pre-process	**In-process**	**In-process**	**Post-process**
• Architecture of fabric (Stacking Sequence, weave style, Number of layers, GSM, porosity, • Fiber Orientation • Different materials (GFRP, CFRP, KFRP) • Compaction cycle • Compaction pressure • Effect of gravity • Effect of HPM • Membrane usage • Effect of inlet tube diameter and length • Height of resin supply • Double vacuum bag/ silicon bag • Tube diameter • Part geometry • Human factor • Resin properties • (Viscosity, Surface tension, Contact angle) • Degassing • Number of inlet ports & vents	• Flow front • Flow rate • Post filling time • Viscosity of resin • Mold temperature • Inlet/Injection pressure • Outlet vacuum • Amount of resin supply • External temperature • Applying pressure after closing inlet • Pressure drop • Magnetic compaction • Bleeding/ • Flushing after impregnation	• Resin pressure • Preform thickness during the flow • Filling/ infusion time • Viscosity of resin • Saturated and unsaturated permeability • Flow velocity • Flow rate • 1D, 2D, 3D permeability • Thickness variation post filling	• Tensile strength/ • modulus • Bending strength/ • modulus • Impact strength • Flexural strength • Hardness strength • ILSS • Density of fiber • Weight fraction • Fiber volume fraction • Panel thickness • Void content • Short beam shear test • SEM- swelling of fiber • Opening displacement curve • Wear properties • Surface defect • Shrinkage

The feasibility of using natural fiber as a reinforcing material in composites is well recognized in the literature review due to its biodegradability and weightlessness.

During Resin infusion process the reinforcement known as preform is subjected to a complex deformation history. During the **pre-filling,** vacuum is applied and the pressure difference between the cavity and atmospheric pressure increases. The reinforcement is subjected to **dry compaction**. The rate of dry compaction depends on how much pressure difference is allowed to increase. During **the filling stage** before the fluid is injected the preform will creep that is the FVF increases with constant pressure. In filling stage, also known as **transition state or unsteady state** pressure is partly carried by fluid and partly by the vacuum. Before the flow condition is stabilized, flow behavior would depend upon the distance up to which the flow front has reached and time. This is a transient condition, and the flow behavior is characterized by transient or unsaturated permeability.

During the **saturated flow also called as bleeding stage** preform is subjected to **wet unloading**. When the resin flows through a porous fabric preform, local resin pressure increases, because of this, compaction pressure decreases, fabric thickness increases, permeability of the preform increases and flow deviates from the RTM process where the thickness is constant due to two solid walls.

During the **post filling or steady state** the permeability decreases as fabric layers are filled with resin. The inlet amount of resin becomes equal to outlet and wet compaction of fabrics take place. Some preforms, typically those made of compact bundle of several thousand fibers woven or stitched together, exhibit dual scale of porosity a) pours between tows fill first (by viscous pressure) and finer pours between the fibers within tows (by capillary force). The fluid flow through the porous preform is mainly caused by two forces: capillary and viscous. At small flow rate, the capillary forces dominate the viscous forces, causing the fluid to fill the bundles instead of filling the large gaps between the bundles. At the large flow rate, viscous forces dominate the capillary force and fill the big gap between bundles. Resin moves inside the fabric by a) mechanical or injection pressure b) Capillary pressure c) vacuum pressures d) gravity pressure e) viscous force.

2.9 IDENTIFICATION OF RESEARCH GAP

Based on research review and findings following research gaps have been identified.

Most studies were available for conventional high strength fiber based PMC. Looking into this, there is a scope to develop - high strength, high fiber volume fraction (HFVF), natural fiber based FRC using VARTM process by examining the various parameters as mentioned in Table 3.

In VARTM, during infusion process, natural fiber behaves differently than synthetic fiber. There is a scope to understand the phenomena occurring during resin infusion in fabric made up of natural fibers.

Few studies were available for VARTM technique to get HFVF -PMC. However, major issue was to optimize the process parameters for increasing fiber volume fraction.

Not much investigation was performed to study the effect of gravity to improve quality of laminate. There is scope of improvement after including effect of gravity by inclined impregnation.

The major challenges faced while manufacturing parts by VARTM process includes control of part thickness variation; minimization of void content, maximization of fiber volume fraction and mechanical properties.

Very few researchers have adopted the concept of design of experiments to study the effect of parameters on above challenges. Almost none has explained practical difficulties while manufacturing VARTM process which leads to make it a trial and error process.

Thus, the proposed research work is focused on developing indigenous experimental set up to manufacture composite made up from natural fibers. This will help to investigate effect of various parameters on controlling void content, part thickness, and fiber volume fraction, physical and mechanical properties for VARTM process.