Study on the high-speed RTM to reduce the impregnation time for carbon/epoxy composites

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Keywords: Resin transfer molding (RTM), Carbon fiber reinforced composite, Computational fluid dynamics (CFD), Permeability

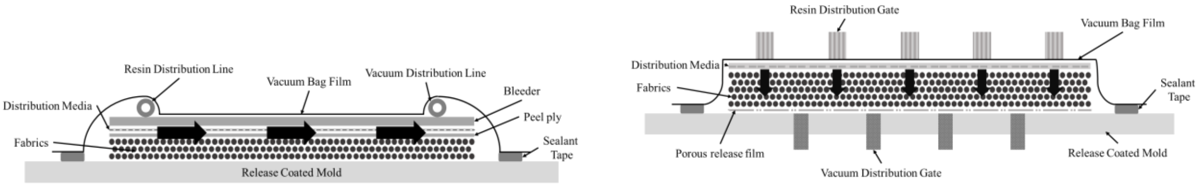
Abstract

Resin transfer molding (RTM) process is widely used to fabricate carbon fiber reinforced composite structures. Especially, it is suitable for manufacturing thin plate structures due to low processing cost, excellent dimensional control, tolerance sensitivity and etc. The conventional RTM processes has a limit to produce large structures due to significantly increasing impregnation time in proportion to the area of product. In this study, composite plate structures were fabricated by using new high-speed RTM process to reduce the impregnation time. The key idea of this method is to change the resin flow direction from in-plane to through-thickness of the preform. A computational fluid dynamics (CFD) simulation was introduced to investigate the impregnation state of preform with respect to flow time. And the simulation results were compared with experiment results.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) are a class of advanced materials that have been developed for a variety of applications in areas of high technology [1, 2]. According to increasing use of CFRPs in various fields, there is a growing interest in manufacturing methods of CFRPs. Most commonly employed techniques to manufacture CFRP structures are hand lay-up, filament winding, pultrusion, and resin transfer molding (RTM) [3, 4, 5].

RTM process has been widely used in various industries, because products can be manufactured easily and the cost for manufacturing is lower than that of other manufacturing method [6]. Conventional RTM process is shown in Fig 1 (a). The carbon fiber preform is placed on the top of the mold and is covered by a distribution medium (DM) with a high in-plane permeability to accelerate the in-plane flow. Resin is moving from injection line to vacuum line when vacuum is applied to the preform. If preform area increases, resin transfer time also increases and dry spot can be easily generated [7].



(a) (b)

Figure 1. Diagram of RTM for composite; (a) Conventional RTM process, (b) New high-speed RTM process using multi vacuum gate.

Impregnation time at the RTM process can be derived from Darcy's law with respect to fiber permeability [8].

$$u = -\frac{K}{\mu} \nabla P \tag{1}$$

Where u is flow flux, K is Permeability, μ is the fluid viscosity, and ∇P is pressure gradient. From equation (1), the impregnation distance can be derived as below.

$$L^2 = \frac{2K\Delta Pt}{\phi\mu} \tag{2}$$

Where L is flow distance, ΔP is the pressure difference between the injection gate and the flow front, t is flow time, and ϕ is porosity. If pressure is constant, flow distance can be expressed to an exponential function with respect to flow time, in other words, flow velocity remarkably decreases as flow time passes. Therefore, total impregnation time increases due to low flow velocity. Accordingly conventional RTM processes have limitation to fabricate large area structures.

In this study, new high-speed RTM process was introduced and its configuration with multi vacuum gates inducing resin flow from top to bottom through the preform thickness direction was shown in Fig. 1(b). The key idea in this method is to change the resin flow direction from in-plane to through-thickness of the preform. Impregnation velocity of through-thickness RTM can be faster than existing conventional RTM due to their short impregnation distance. However, the suggested RTM process can generate dry spot at the center of four neighboring vacuum gates because pressure distribution around each vacuum gate is developed with circular contour shape. Therefore, CFD simulation with respect to vacuum gate distribution and its size was performed to achieve the fast impregnation without any dry spot, and the simulation results were confirmed by experiment results.

2. CFD simulation

2.1. Permeability measurement

Through-thickness and in-plane permeability were measured to obtain the reliable input for the CFD simulation. Preform was made up 12 sheets of 3k plane woven carbon fabric (CF-3327EPC, Hankuk Carbon, Korea). Flow rate corresponding to the pressure in the preform was measured by using the flow sensor installed in the pore size analyzer (Porometer 3G, Quantachrome, INSTRUMENTS, USA). Permeability of through thickness direction was calculated by equation (1).

Permeability of in-plain direction was measured by radial flow experiment [9]. The fluid was injected into the mold under a predetermined air pressure. During the test, a video camera installed above the permeability test mold recorded the impregnation distance as time goes by. The permeability of in-plain direction at radial flow experiment was calculated by equation (3).

$$\boldsymbol{K} = \frac{\mu}{2tP_0}\left[r^2 \ln\left(\frac{r}{r_0}\right) - \frac{1}{2}(r^2 - r_0{}^2)\right] \qquad (3)$$

Where t is injection time, P_0 is pressure at the inlet, r_0 diameter of inlet and r is diameter of radial flow front.

2.2. Simulation model

Through thickness RTM model with respect to the number of vacuum gate was shown in Fig 2. Total area was fixed to 300x300 mm^2 and the vacuum gate diameter and interval with respect to number of vacuum gate are shown at Table 1. Total vacuum gate area was fixed to 50.26 mm^2 in order to apply the equal vacuum pressure to the all the gate regardless of the number of vacuum gate. Accordingly, the diameter of vacuum gate depends on the number of vacuum gate. The area of pressure outlet which is same with total area of the vacuum gates was designated at the center of bottom plate. The empty space was made between the top and bottom plate in order to apply identical vacuum pressure to the all vacuum gates. The top surface of preform which the epoxy resin was supplied was defined as a “pressure inlet” boundary condition.

Code	Number of vacuum gate	Vacuum gate diameter	Interval between vacuum gates	Total vacuum gate area
4VG	2x2	4mm	150mm	50.26mm^2
16VG	4x4	2mm	75mm	
36VG	6x6	1.33mm	50mm	
64VG	8x8	1mm	37.5mm	
100VG	10x10	0.8mm	30mm	

Table 1. Vacuum gate diameter and interval with respect to number of vacuum gate.

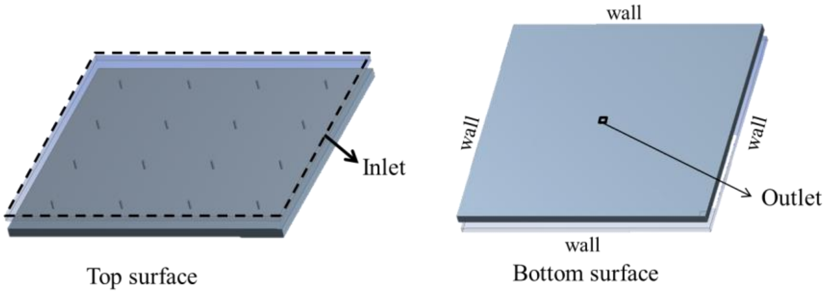


Figure 2. Schematic diagram of CFD model of through thickness RTM.

Preform is considered to be anisotropic porous medium, and viscous resistance and inertial resistance value are used to cell zone condition from permeability. The most relevant CFD settings are summarized in Table 2.

Surface monitor whose area is 1x1 mm^2 was set up to confirm the mass flow rate and volume flow rate at the position of vacuum gate and the center of four neighboring vacuum gates which dry spot easily occurs.

CFD parameter		
General	solver: pressure-based/transient	
Fluid materials	Air	Viscosity: 0.0179 cP, Density: 1.22Kg/m^3
	Epoxy	Viscosity: 178 cP, Density: 1046 Kg/m^3
Cell zone condition	Viscous resistance	D_{11}, D_{22}: 6.6658e+08, D_{33}: 4.697e+09
	Inertial resistance	D_{11}, D_{22}: 1046.25, D_{33}: 258713
Boundary condition	Inlet pressure: 0.1 MPa, Outlet pressure: 0 Pa (vacuum)	
Model	Model: volume of fluid Number of phase: 2 (phase 1: air / phase 2: epoxy)	
Solution	Scheme: PISO	

Table 2. CFD parameter

3. Experimental

3.1 Through-thickness RTM process

Preform used in this experiment consists of 12 sheets of 3k carbon fabric, and preform dimension is 300 X 300 X 3 mm^3. The epoxy resin is a bisphenol-A/F liquid with an aliphatic glycidyl ether (YD-114F, KUKDO Chemical Co. Ltd., Korea), and the hardener is ??? (D-230, KUKDO Chemical Co. Ltd., Korea). Schematic diagram of the through-thickness RTM experiment is shown in Fig 3. 5mm acrylic mold having multi-holes is used to embody multiple vacuum gates simply. And peel ply is laid down bottom of preform to visualize resin impregnation state. The resin layer is formed on the preform enclosed by vacuum bag by applying pressure to the resin vessel, and then impregnation process starts with applying vacuum. At least twice of each CFD analysis models (GV4, GV16, GV36 and GV64) were tested.

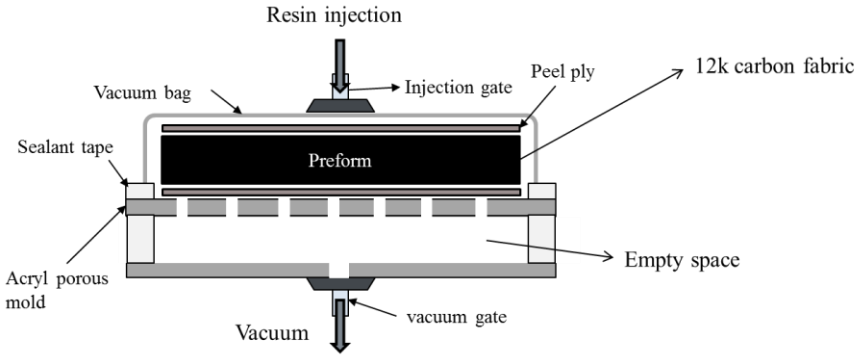


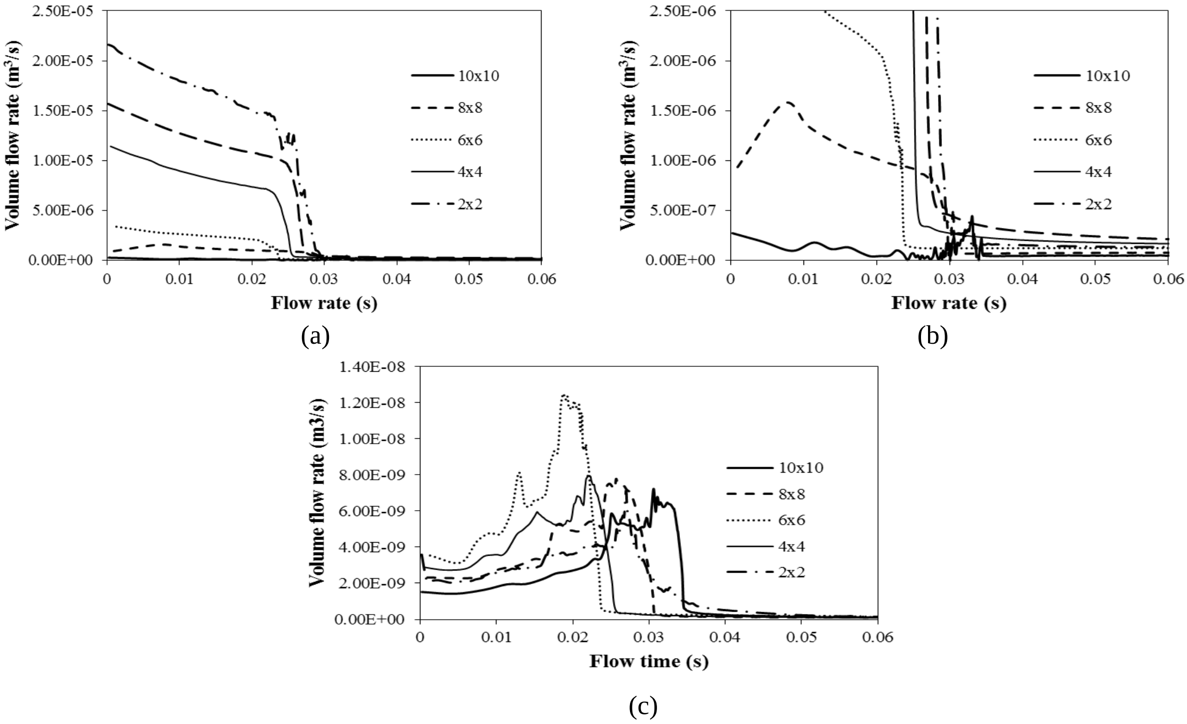
Figure 3. Schematic diagram of thethrough-thickness RTM process

3.2 Conventional (in-plane) RTM process

Conventional RTM process whose resin flow direction is in-plane was performed to compare the total impregnation time with through-thickness RTM process. Resin distribution tube and vacuum distribution tube were put on both ends of preform for in-plan transfer, and bleeder was put on the top of preform. All of test condition but the flow direction were equal to through-thickness RTM.

4. Results and discussion

Fig 4 and Fig 5 present graphs of volume flow rate and mass flow rate with respect to the location of the flow meter. Volume flow rate and mass flow rate calculated by using the function of flow meter in the software include the information of two phases, air and the resin. But, mass flow rate and volume flow rate depend on each resin flow and air flow caused by density difference of air and epoxy resin, respectively. Therefore, epoxy resin flow was calculated from mass flow rate graph. And also air flow was obtained from volume flow rate graph. Fig 4 (a) presents volume flow rate at vacuum gate as time goes by. All of models tended to greatly reduce volume flow rate within 0.04 seconds. Volume flow rate is greatly reduced, thus, because inside air of RTM model comes out completely. Degassing time which air comes out from the preform completely was defined by intersection point of two trend lines. Volume flow rate of previous degassing time increased with respect to proportion with diameter of vacuum gate. On the other hand, degassing time is out of proportion with diameter of vacuum gate, VG36 model showed the fastest impregnation velocity and the slowest impregnation time was observed at VG100 model. Volume flow rate at the center of four neighboring vacuum gates shown in Fig 4 (c) tends to greatly decrease after air comes out from the preform completely. Degassing time of each model was almost same at the vacuum gate. However, before degassing time, VG36 model showed most significant volume flow rate which was out of proportion with vacuum gate diameter.

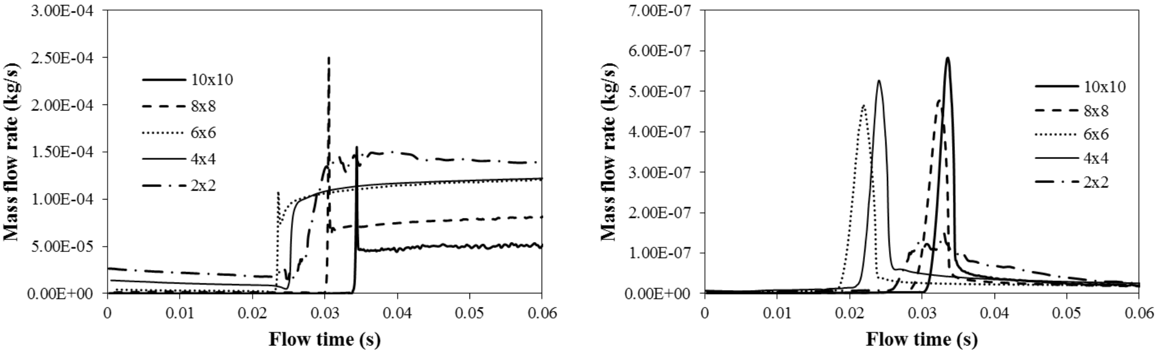


(a) (b)

(c)

Figure 4. Volume flow rate with respect to the location of the flow meter; (a) vacuum gate, (b) magnification of vacuum gate result , (c) center of four neighboring vacuum gates

Fig 5 (a) presents mass flow rate at vacuum gate with respect to flow time. When resin flow reaches to the vacuum gate, mass flow rate is suddenly increased. Therefore, resin impregnation started time was defined when mass flow rate rapidly increase. And also it was calculated by intersection of two trend. Before resin impregnation starts, the mass flow rate increased in proportion to the diameter of the vacumm gate. However, VG36 showed the fastest and VG100 showed the slowest impregnation beginning regardless of the diameter of vacuum gate. Fig 5 (b) is result of mass flow rate measured at the center of four neighboring vacuum gates. Mass flow rate rapidly increased compared to that measured at vacuum gate, and then mass flow rate tend to decrease again. Mass flow rate decrease again after rapidly increase compared to the graph measured at vacuum gate. Resin impregnation started time appears at the center of four neighboring vacuum gates as resin flows arrived at the bottom surface. However, compared to mass flow at the vacuum gate, mass flow rate greatly decreased again because the resin already reached to the bottom surface. Also that VG36 showed the fastest and VG100 showed the slowest mass flow rate at the vacuum gate. Generally, the pressure gradient decreases as distance from vacuum gate increase because pressure distribution around each vacuum gate is developed with circular contour shape. However, mass flow rate at the center of four neighboring vacuum gates was not proportional to number of vacuum gate as shown in Fig 5 (b). This means wall area of total holes increases according to increasing number of holes, namely flow velocity decreases as the flow resistance increase. Air degassing time and resin impregnation started time are summarized on table 3 with respect to the RTM model.



(a) (b)

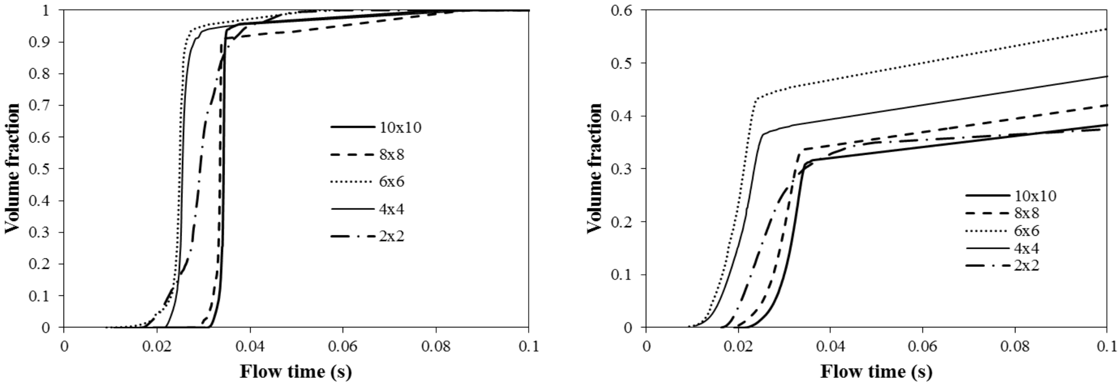
Figure 5. Mass flow rate with respect to the location of the flow meter; (a) vacuum gate, (b) center of four neighboring vacuum gates

	Air degassing time		**Resin impregnation started time**	
	Vacuum gate	**Center**	**Vacuum gate**	**Center**
VG100	0.03460	0.03511	0.03392	0.03108
VG64	0.02987	0.03066	0.03107	0.02784
VG36	0.02402	0.02383	0.02324	0.01897
VG16	0.02583	0.02583	0.02499	0.02165
VG9	0.02753	0.02800	0.02657	0.02354
VG4	0.02945	0.02995	0.02684	0.02589

Table 3. Summary of air degassing time and resin impregnation started time

Fig 6 shows the resin volume fraction at the vacuum gate and the center of four neighboring vacuum gates with respect to flow time. Measurement location of volume fraction is identical with measurement location of surface monitor. Fig 6 (a) indicates resin volume fraction at the vacuum gate with respect to flow time. All of models tend to rapidly increase resin volume fraction from 0.02 to 0.04 seconds. And also the preform located on the vacuum gate was completely impregnated before 0.1 seconds. On the other hand, in case of Fig 6 (b) shown resin volume fraction with time at the center of four neighboring vacuum gates, all of models at the center of four neighboring vacuum gates were not completely impregnated until 0.1

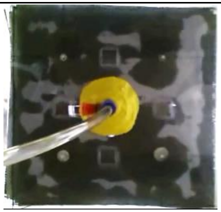
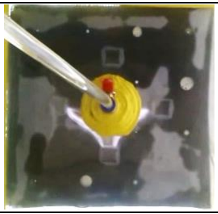
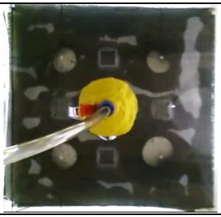
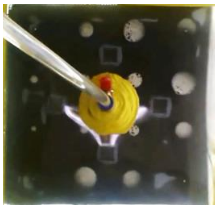
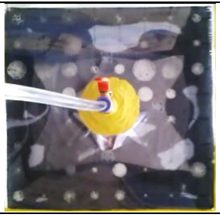
seconds and degree of impregnation was significantly different with respect to model. Initial resin impregnation started time were faster in order VG36, VG16, VG4, VG64 and VG100, which is same with mass flow rate result. However, VG4 showed the lowest degree of impregnation around 0.1 second.



(a) (b)

Figure 6. The resin volume fraction graph with respect to flow time; (a) Vacuum gate, (b) Center of four neighboring vacuum gates

Fig 7 shows impregnation state of through-thickness RTM experimental results for 100 sec with respect to number of vacuum gate. The dark parts show totally impregnation area. At the beginning of flow time, VG36 had better impregnation state than the others. Otherwise, in case of the VG4, each edge side was not impregnated within 100 sec. From the results, we confirmed the tendency of the experimental results was well matched with the CFD simulation results.

	VG4	VG16	VG36	VG64
5s				
10s				
20s				

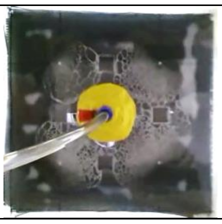
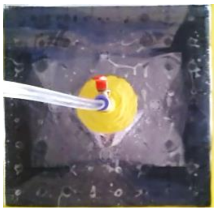
100s				

Figure 7. The experiment results; impregnation state of through-thickness RTM experimental for 100 sec with respect to number of vacuum gate.

5. Conclusions

In this work, new high-speed RTM process using multi vacuum gate was proposed. Impregnation state was investigated by CFD simulation with respect to flow time. And the simulation results were compared with experiment results. From the results, superiority of new high-speed RTM process was demonstrated and optimum distribution of the vacuum gate was suggested.

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