Numerical simulation on the permeability of non-crimp Carbon fiber epoxy using out-of-autoclave manufacturing method

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Abstract. Composites made using Resin Transfer Molding (RTM) processes have attractive properties to the aerospace and automotive industries because they can produce complex composite parts with good surface finishing. However, it still has a problem filling a large part with high fiber content at low injection pressure. Therefore, during the experiment, resin flow has to be the primary concern. This work presents a resin flow simulation of two types of mold where it will visualize the manufacturing process without actually doing it. Numerical simulation for the RTM manufacturing process is attempted by using Fluent-Ansys. It allows us to simulate the resin flow through the porous medium and obtain the total mold filling time and volumetric flow rate. It will lead to an explanation of the strength of the composite produced. Several assumptions and techniques are used to simplify the problem. Some variables, such as porosity and pressure injection, will be varied to see the effect of those variables on the RTM manufacturing process. According to the simulation result, porosity and pressure injection affect the RTM manufacturing process, especially for resin filling time and volumetric flow rate. The increase of porosity will increase the flow time, while pressure injection will decrease the flow. It happens due to how easy the resin flows through the porous medium, and the total area needs to be filled by the resin. This work is validated by comparing the obtained results with analytic solutions for a specific mold of Darcy’s law.

Keywords: Resin transfer molding, porosity, pressure injection, analytic solution, Darcy’s law

1. Introduction

Since the birth of aviation, designers have continuously endeavored to improve the lift to weight ratios of aircraft. Composite materials have played a significant role in weight reduction. Therefore, the development of lightweight material has been attracting attention. The use of composite is increasing to develop lightweight and high-strength vehicle components as these enable designers to overcome the barriers created by using metals. Many companies are competing against each other to offer the best composite material. Producing a composite that has good quality, especially for the aerospace industry, is usually done by the autoclave method. However, this method needs a higher cost than it needs to be [1]. Thus, many innovations are made to produce a composite with a low cost. One of them is called Out-of-Autoclave. The example of out-of-autoclave is Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM).
The resin transfer molding (RTM) process has been the subject of a great deal of practical and theoretical development for aerospace applications since the early 1980s. For instance, Mitsubishi Regional Jet (MRJ) has been used composite produced by the RTM manufacturing process, where it offers impressive operating costs with good efficiency. RTM suits to manufacture high quality of complex products, and the products have high fiber content. In the forming process, there are less volatile components and little environmental pollution. With less investment and high production efficiency, the production automation is adaptable for this process [2].

The strength of the composite produced by RTM is dependent on the impregnation of the resin flow through the fiber. Permeability defines the resistance to the resin flow. Permeability is a reinforced medium property used to measure (quantify) how easy a fluid can pass through a porous medium [3]. Therefore, Permeability is a property that needs to be the primary concern.

In this paper, the resin flow process in the RTM manufacturing process has been simulated using FLUENT and the outputs are focused on investigating the effect of variation of porosity and pressure injection to the total mold filling time and pressure distribution that occur during the process. Filling time is obtained and after that, the result will be compared to the result of the analytical method.

2. Analytical Models

To simulate the RTM process; several assumptions are used to simplify the process, such as the resin's density remains constant, assuming the resin as a kind of Newton fluid, viscous force, and surface tension are neglected, type of flow is rectilinear, and curing process is neglected by assuming after full filling, the resin begins to cure.

The basic theory of prediction of the flowing resin is generally modeled as a Newtonian fluid with constant density and viscosity, so the Navier-Stokes equation is valid. However, the common equation used to model the flow of resin in Out-of-Autoclave is Darcy's law [4]. It is a simplification of the Navier-Stokes equation. Newtonian fluid flow in porous media is often modeled using a generalized version of the full non-linear Navier-Stokes equations that include additional terms describing the resistance to flow due to the porous matrix. Darcy's law can be expressed as:

$$ q = -\frac{K}{\mu} (\Delta P) \quad (1) $$

where $q$ is the flow rate, $K$ is the permeability of porous medium, $P$ is the pressure gradient, and $\mu$ is the viscosity. It assumed that there is no movement perform during the flow process, therefore continuity condition is applied.

$$ q = \frac{dx}{dt} \quad (2) $$

since,

$$ v = \frac{q}{\phi} \quad (3) $$

where $v$ is the velocity of the fluid and $\phi$ is the porosity. Therefore,

$$ v = \frac{dx}{\phi \, dt} \quad (4) $$

Additional assumption like constant pressure is applied due to the constant flow rate of the resin supply system.

$$ \nabla P = \frac{\partial P}{\partial x} = \frac{p}{x} \quad (5) $$

By substituting and doing the integration to Darcy’s law, the formulation of the total filling time, in this case, can be obtained as follow:

$$ t = \frac{x^2 \mu}{2 \, KP} \quad (6) $$
3. Simulation Model

The RTM process is carried out on two types of two-dimensional mold such as rectangular and rectangular with hole. Several variables are varied. Several variables are varied, such as porosity (0.4, 0.6, and 0.8) and pressure injection (70000 Pa, 100000 Pa, and 130000 Pa). Other variables, like permeability, air properties, and resin properties, will remain constants [5].

| Table 1. Fixed-Parameter |
|--------------------------|
| Fixed Variable          | Magnitude  | Unit     |
| Air density             | 1.225      | Kg/m³    |
| Air viscosity           | 1.7894 × 10⁻⁵ | Kg/ms   |
| Permeability            | 3.89 × 10⁻⁹ | m²       |
| Resin density           | 916        | Kg/m³    |
| Resin viscosity         | 0.7115     | Kg/ms    |

There are 2 types of process such as mechanical modelling and FLUENT. The mechanical model comprises of engineering data, geometry, and model while Fluent comprises of problem setup, solution, and result.

3.1. Mechanical Model

This process allows us to create the mold's geometry, determine the type of material of the mold, and perform the meshing. Rectangular and rectangular with hole mold are built with dimension 1 x 0.5 m and a radius of 0.1 m. Non-crimp carbon fiber is applied as the mold's material and there are three meshing sets such as general mesh, edge mesh, and face mesh with size 5 mm.

![Figure 1. Mold geometry models](a) Rectangular (b) Rectangular with Hole)

3.2. Fluent program

The FLUENT is set as 2D double precision solver. The specific settings in FLUENT are as follows:

- a. The boundary condition is defined as follows, a pressure inlet condition is defined at the inlet surface, and the value of pressure inlet defines the pressure injection will be used while a pressure outlet at the outlet surface.
- b. The Reference Values task page is set as default.
- c. The pressure coupled equations of half implicit method (i.e., SIMPLE algorithm) are adapted to the solution. The under-relaxation factor and discrete format are the same as the default value.
- d. The convergence accuracy during the calculation is 0.0001 up to 0.000001.
- e. The time step and iteration are 0.1 and 10, respectively.
- f. The gravitational effect is neglected.
- g. The number of steps will be varied according to the porosity and pressure injection used.
- h. Input the process conditions, including the viscosity and density of resin, the porosity of porous media and its viscous resistance and inertia resistance to resin, and the boundary conditions. Then initialized, and set a solution animation to monitor the volume fraction of resin, calculated at last.
In this case, the resin is injected from the left boundary side of the mold (Figure 2), then resin (epoxy) is injected into the mold under a constant injection pressure. The interaction between phases like surface tension is neglected to simplify the problem. The whole zone of the mold is defined as fluid.

Next, input others variables such as viscosity and density of the resin, porosity, permeability, and boundary condition. In this case, pressure injection at the inlet is varied as mention previously while at the outlet, the pressure is set as a constant 0 Pa while the other boundaries are set as atmospheric pressure. Then do the initialization and set a solution animation to monitor the volume fraction of resin.

VOF method is used to simulate the RTM process where has been frequently used to solve moving boundary problems in a fixed mesh. Furthermore, it is representative of the boundary tracking method. For the RTM process's numerical simulation, the resin flow front position in the mold is obtained by the VOF method [6].

4. Results dan Discussions

4.1. Simulation results

4.1.1. Rectangular mold

Figure 3 shows the resin filling process with porosity 0.4 and pressure injection 70000 Pa done by FLUENT. It took 520.2 seconds to fill the whole mold with the resin. There is no difference in the visualization of the resin filling process for other pressure injection and porosity configuration, except for the total time for the resin to completely fill the mold. Table 2 below shows the results of the resin filling time for each configuration.
Figure 3. Resin filling simulation of porosity 0.4 and pressure injection 70000 Pa

| Porosity | Total Resin Filling Time (s) |
|----------|-----------------------------|
| 0.4      | 520.5 381.7 346             |
| 0.6      | 785.8 559.8 454.7           |
| 0.8      | 1044.6 735.8 544.7          |

Moreover, the figure below shows the effect of porosity and pressure injection difference on the total resin filling time.
Other output results can be obtained through this simulation is volumetric flow rate. Here’s the graphs show the volumetric flow rate for each pressure injection.

**Figure 4.** Rectangular resin filling time (a) 0.8 (b) 0.6 (c) 0.4
According to figure 4, it shows the effect of porosity and pressure injection on resin filling time. Increasing the porosity took a long time for the resin to fill the whole mold while increasing the pressure injection shortens the total resin filling time. At porosity 0.4, overall, the resin filling processes do not give a significant effect (the lines almost coincide) if it is compared with porosity 0.8. However, the total resin filling time is still affected by it. It is due to the increasing area needs to be covered by the resin. Porosity is the ratio between void area and total mold area. Since the total mold area is constant, the porosity value here will affect the void area. By increasing the porosity in this case, the total void area is increasing.

Figure 5 explains the reason why increasing pressure injection shortens the total resin filling time. It is due to the increasing volumetric flow rate as the effect of increasing pressure injection where it will lead to the increasing of the pressure gradient. Therefore, it shortens the resin filling time process.

Figure 5. rectangular volumetric flow rate (a) 0.8 (b) 0.6 (c) 0.4
4.1.2. Rectangular with hole mold

Figure 6. Resin filling simulation of porosity 0.4 and pressure injection 70000 Pa

Figure 6 rectangular with hole shows the resin filling process with porosity 0.4 and pressure injection 70000 Pa done by FLUENT. It took 597.8 seconds to fill the whole mold with the resin. Same as rectangular mold, there is no difference in the visualization of the resin filling process for other pressure injection and porosity configuration, except for the total time for the resin to completely fill the mold. Table 3 below shows the results of the resin filling time for each configuration.

Table 3. Rectangular with hole total resin filling time

| Pressure Injection | 700 kPa | 1000 kPa | 1300 kPa |
|-------------------|---------|----------|----------|
| Porosity          | 0.4     | 0.6      | 0.8      |
| 0.4               | 597.8   | 456.2    | 402.3    |
| 0.6               | 842.3   | 762.2    | 776.6    |
| 0.8               | 1492.4  | 1107.3   | 1125.1   |
Figure 7. Rectangular with hole resin filling time (a) 0.8 (b) 0.6 (c) 0.4
Figure 7 shows the effect of pressure injection and porosity on rectangular with hole on resin filling time. When the pressure injections are varied into 70000, 100000, and 130000 Pa, the total resin filling time reduces. It significantly reduces at porosity 0.8 compared with other porosities. When the porosity is varied into 0.4, 0.6, and 0.8, the total resin filling time increases the same as the rectangular mold.

Figure 8 shows that the volumetric flow rate of rectangular with a hole is fluctuated due to the separation flow when the resin flow reaches the hole. Same as the rectangular, the volumetric flow rate escalates by increasing the pressure injection. The porosity difference does not significantly affect the volumetric flow rate for the same pressure injection, according to figure 8.

Not only porosity and pressure injection affect the RTM process. In this case, other variables, like the geometry of the mold, also affect the RTM process. Comparing data obtained from rectangular and rectangular with a hole can be concluded that different mold will increase the total resin filling time at the same pressure injection. It is due to the complexification shape where related to the type and the number of flows used in the process. More complex, there will be more flow definitions that need to be applied. In this case, rectangular mold is a rectilinear flow while rectangular with hole mold is rectilinear initially, but when it reaches the hole, the flow will separate into two flow.

As a consequence, the type of flow is changing. There will be flow in the y-direction. Therefore, it will affect the resin filling time. Moreover, the effect of mold variation on the volumetric flow rate is for the rectangular mold, the volumetric flow rate is like a curve, while for the rectangular with hole mold, fluctuated appears. It is due to the separation flow occurs when the flow reaches the hole. The effect of porosity difference does not significantly affect the volumetric flow rate for both molds. In contrast, the effect of pressure injection difference significantly affects the volumetric flow rate. On the other hand, the volumetric flow rate for rectangular with a hole is not significantly affected by the pressure injection difference.

4.2. Analytical results

Analytical result is done to validate the simulation done by FLUENT. this method is limit only for rectangular mold due assumption that used.
Table 4. Rectangular analytical result

| Pressure Injection (Pa) | Porosity | Rectangular Mold | Total resin filling time of analytical solution (s) |
|-------------------------|----------|------------------|---------------------------------------------------|
|                         |          |                  | 70000                                             |
|                         |          |                  | 100000                                            |
|                         |          |                  | 130000                                            |
| 0.4                     |          |                  | 522.6                                             |
|                         |          |                  | 365.8                                             |
|                         |          |                  | 281.4                                             |
| 0.6                     |          |                  | 783.9                                             |
|                         |          |                  | 548.7                                             |
|                         |          |                  | 422.1                                             |
| 0.8                     |          |                  | 1045.2                                            |
|                         |          |                  | 731.6                                             |
|                         |          |                  | 562.8                                             |

Table 5. Rectangular comparison error result

| Pressure Injection (Pa) | Porosity | Rectangular | Error (%) |
|-------------------------|----------|-------------|-----------|
|                         |          | 70000       | 100000    | 130000    |
| 0.4                     |          | 0.40        | 4.16      | 18.17     |
| 0.6                     |          | 0.25        | 1.98      | 7.17      |
| 0.8                     |          | 0.05        | 0.57      | 3.32      |

From table 4 and 5, it shows the comparison between analytical and numerical solution. For pressure injection 70000 and 100000 Pa, the errors are still low (below 10%), while at pressure injection 130000 Pa at porosity 0.4, the error exceeds 10%. Many things have been done to reduce this error, but it showed the same result. The error possible occurs due to the boundary condition setup. Boundary condition setup is used to guess the initial pressure and velocity at the inlet. Boundary condition setup has many possibilities; it is due to the pressure injection and operating pressure. Since in this experiment, the operating pressure is set as a constant (atmospheric condition). Therefore, the initial pressure and velocity guessing by boundary conditions are incorrect because operating pressure is set up in Fluent is not applicable or correct for in this case.

5. Conclusions
In this research, current work is mainly focused on the effect of pressure injection, porosity, and type of mold on the RTM manufacturing process. Several parameters are still constant to simplify the problem and simulation procedure. For instance, the value of permeability is set as constant to simplify the problem, and that is why non-crimp carbon fiber is used. Future work involves presenting all the variables that might affect the process, such as permeability is as a function, use other types of flow, and experiment has to be done to validate the simulation results.

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