Abstract. Vacuum assisted resin infusion (VARI) is a process applied to manufacture large structures of composite materials, such as aircraft wing and fuselage skins, but the process parameters are designed by experience or lots of experiments. In this paper, the filling process of VARI for composite fuselage skin was analyzed based on simulation and optimized location of resin inlet ports. Firstly, we made 3D model of fuselage skin and simulated impregnation process. Secondly, we determined the location and quantity of resin inlet ports based on simulation results. The simulations showed that it is advisable to reduce the filling time not only by adding the resin inlet quantity, but also choosing optimal locations.

1. Introduction

The fiber-reinforced plastics are composite materials which combine low weight, high mechanical strength and good corrosion resistance [1-3]. Nowadays, the composite materials are widely used in the aerospace industry due to its characteristics and are replacing the traditional engineering materials [4].

In the aviation industry there is a drive toward more sustainable and low-emission aircraft due to market constraints and customer needs [5-7]. The airline operators are demanding for reduction in operating cost, since there are concerns about the rising cost fuel. Consequently, aircraft manufactures are trying to build lighter aircraft in order to save fuel. Therefore aircraft manufacturers have been gradually increasing its reliance on composite materials. For example, the Boeing 787 fuselage is built in five main sections consisting of composite material that account for 50% of the aircraft’s total structural weight.

In our work the fuselage skin of a light aircraft which is made of composite materials based on carbon fiber-reinforced plastic (CFRP) that made it possible to simultaneously provide strength and lightweight construction. For the production technology vacuum assisted resin infusion (VARI) process is used. This process is a very attractive composite manufacturing process since large structures such as fuselages and aircraft wing can be fabricated in a cost effective manner [8-10].

The quality and properties of manufactured part is influenced by several parameters. In composites for special application, the fiber reinforcing materials is set up by a laminate of multiple layers stacked with different orientations according to a stacking sequence. The mechanical properties of the resulting composite in the load direction depend on the stacking sequence of laminate. Regarding to the resin injection process, the locations and quantity of the inlet gates and outlet vents of the mold
affect directly the pressure inside the mold, the filling time and the successful and complete impregnation of the laminate by the resin [8]. The prediction of flow behavior during the filling mold stage is critical to obtain a high quality product and develop an efficient process with sufficient filling strategies to avoid dry areas and decrease the mold filling time. Since the traditional trial-error methods are costly and time consuming, simulation emerges as an effective alternative to design and optimize the molding process. To carry out accurate simulation modeling models is required knowledge of several experimental parameters such as the geometry of the mold, the resin properties and the porosity and permeability values of the fiber materials [1, 11]. Therefore, in our study to simulate the impregnation technology, the PAM-RTM software is used, which allows to determine the binder inlet channels, the duration of impregnation process, etc.

Present work studies the flow of resin through a carbon plastic laminate set up by multiple layers during the resin injection filling stage of a vacuum infusion process by using simulation software PAM-RTM. The aim of our work is to study the resin injection time of composite fuselage skin based on different viscosity of binding material and to define the optimal quantity and location of resin inlet ports based on simulation results. The resin infusion method procured from simulation can effectively avoid the high cost caused by the trial and error method.

2. Methodology

The numerical simulation of the VARI process in PAM-RTM software implies the modeling of three categories of physical phenomena: the resin flow through the fiber bed, the thermal analysis of heat exchanges in the part and with the mold, and finally, the chemical reaction of the resin. The flow of resin is governed by Darcy’s law, which states that the flow rate of resin per unit area is proportional to the pressure gradient and inversely proportional to the viscosity of the resin.

2.1. Materials

The model of our study is an aircraft fuselage skin made of carbon fiber plastics. This composite fuselage is produced using vacuum assisted resin infusion process. For the production of composite fuselage skin carbon fabric WL-Blatt 8.3520.80 was used as reinforced materials and the composition of epoxy resin (ED-20), Methyl tetrahydrophthalic anhydride (MTHPA) and Diethylene Glycol (DEG-2) was used as a binder (Table 1). The content of Diethylene Glycol in this composition varied from 5 to 10%, which allowed changing the viscosity of the binder. The choice of this material was associated with its good rheological properties, good mechanical characteristics and low cost [1]. Epoxy resin ED-20 is used in electric and radio electronic industry, aviation, ship and machine-building industry, in the construction industry as a component of potting mixtures and impregnation compounds, sealants, as a binding agent for reinforced plastics.

| Table 1. The physical properties of the binding materials |
|-----------------------------------------------|
| Type of materials                | Content in composition of binder, | Density, kg/m³ | Viscosity (25°C), Pa.s |
|-----------------------------------------------|
| ED-20                            | 100                              | 1130            | 20 – 25          |
| Methyltetrahydrophthalic anhydride (MTHPA) | 80                               | 1320            | 0.03 – 0.05      |
| Diethylene Glycol (DEG-2)         | 5 – 10                           | 1120            | 0.0357           |

As a reinforcement material carbon fabric WL-Blatt 8.3520.80 was used. The characteristics of this kind of fabrics are suitable to use for composite light aircraft fuselage body. Physical-mechanical properties (Table 2) of carbon fabric WL-Blatt are shown in following.
Table 2. Geometrical characteristics of carbon fabrics

| Type of Carbon fabric | Thickness, mm | Liner density, tex | Dry weight, g/m² | Density, kg/m³ | Wrap, thread/cm | Weft, thread/cm |
|-----------------------|---------------|-------------------|------------------|----------------|----------------|----------------|
| WL-Blatt 8.3520.80    | 0.15          | 200               | 204              | 1800           | 5.0            | 5.0            |

One of the most critical factors in setting the boundary conditions of the numerical model is the knowledge of permeability values and porosity of the reinforcing materials, because it influence on the resin flow behavior during resin injection process. The permeability characterizes the relative facility of a viscous liquid to impregnate a porous medium [1-3]. This physical property of the porous medium depends on the fiber volume fraction and on the draping of the plies. In our analysis the fiber volume fraction is 55%. We considered the permeability coefficients in all directions are equal. So, coefficient of permeability for carbon fabric WL-Blatt 8.3520.80 is 9.1x10^-10.

2.2. Finding optimal quantity and location of inlet ports

The geometry of fuselage skin is modeled using FEM software SolidWorks and it is transformed Visual Mesh for meshing (Fig. 1). In meshing process type of mesh element is tri-quad and size of the element is 10 mm. The fuselage model is meshed into 8896 elements. Then the meshed model is imported to PAM-RTM program for the modeling of resin injection process.

Thickness of single layer of carbon fabric is 0.15 mm and the total thickness of fuselage skin is 2.25 mm. So, fuselage skin is composed of 15 layers of carbon fabrics and layup scheme is [0]₁₅.

Boundary conditions of the simulation of VARI are listed (Table 3 [10]). The inlet gate and outlet vent pressures are one atmosphere and vacuum pressure, respectively. The diameter of each inlet gate is 10 mm.

To find the optimal quantity and location of resin inlet ports, we used PAM-RTM software and one of its command GENPORTS. PAM-RTM is a resin injection software module which is used to simulate the injection or the infusion of a resin in a preform. Typically, simulation results reveal:

Table 3. Boundary conditions of the simulation process

| Boundary conditions | During resin filling | Removal of excess resin |
|---------------------|---------------------|-------------------------|
| Inlet gates         | P_{inlet} = 0.1MPa  | \frac{\partial p}{\partial n} = 0 |
| Outlet vents        | P_a = P_{vacuum} = 0 | P_{a} = P_{vacuum} = 0 |
filling time, risk of dry spots appearance or fiber washing, flow front velocity, pressure applied to the mole, porosity level, curing time and temperature and degree of cure evolution.

GENPORT is a very useful tool to define the optimize quantity and location of resin inlet ports. It uses a genetic algorithm to find the optimal configuration of injection ports that minimize fill time. The GenPorts parameters are located in the GenPorts tab of the Numerical Parameter (Fig. 2).

To find the optimal location of resin inlet ports, quantity of ports is provided 2 to 5. The optimal locations generated by the program are shown in the following (Fig. 3).

(a) 2 ports  
(b) 3 ports

(c) 4 ports  
(d) 5 ports

Figure 3. Generated optimal location of resin inlet ports

After defining optimal resin inlet locations generated by GENPORT command of PAM-RTM, resin infusion process is modelled (Fig. 4). During this modelling process, the properties of binding material are different, because viscosity of these materials is based on content of Diethylene glycol (DEG-2).
Based on the simulation results (Table 4), it is showed that increasing of quantity of resin inlet ports logically can reduce resin infusion time. Besides increasing the inlet quantity, increasing the content of Diethylene glycol (DEG-2) also obviously made reduction of resin infusion time 3 – 7%.

However, the larger the number of resin inlets, the longer the installation time of inlet pipes. Therefore, we need to consider the installation time of resin inlet pipe when making vacuum bag. According to many experimental analyses, the installation time of inlet pipe during making of vacuum bag are shown in following (Table 5).

### Table 4. Resin infusion time of fuselage skin base on variable content of DEG-2

| Content of DEG-2 | 2 ports | 3 ports | 4 ports | 5 ports |
|------------------|---------|---------|---------|---------|
| 0%               | 4040 s  | 3810 s  | 3690 s  | 3350 s  |
| 5%               | 3919 s  | 3692 s  | 3582 s  | 3252 s  |
| 10%              | 3760 s  | 3548 s  | 3430 s  | 3117 s  |

### Table 5. Installation time of resin inlet pipes

|                | 2 ports | 3 ports | 4 ports | 5 ports |
|----------------|---------|---------|---------|---------|
| Installation time of binding material inlet pipes | 180 s   | 270 s   | 360 s   | 450 s   |
3. Conclusion
As a result of the research, it was found that resin injection time of vacuum infusion process is depend on the number of resin inlet ports and the content of Diethylene glycol (DEG-2), which reduces the viscosity of resin without losing mechanical properties. Increasing of resin inlet port can reduce resin infusion time 3 – 9 %, but at the same time it can increase installation time of resin inlet ports. Therefore, we can adjust the reduction of impregnation time by adding more amount of Diethylene glycol within limited range (0 – 10%). In this way we can improve the vacuum infusion process for the production of large-sized structures.

In this paper, the filling stage of VIP for composite aircraft fuselage skin was systematically studied by simulation in order to provide optimal location and quantity of resin inlet ports. We selected the best number of resin inlet and their locations based on filling simulation under variable composition of binders. Simulation process was detailed described and verified by the optimization process of practical fuselage skin. Estimation of resin infusion time for large-sized structures such as fuselage skin is necessary because during long time resin infusion some properties of resin could be lost. So, by using simulation model, we can estimate resin injection time and can reduced it by choosing optimal location of resin inlet ports.

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