ONLINE FLOW MONITORING SYSTEM DEVELOPMENT FOR THE RESIN TRANSFER MOULDING PROCESS

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Abstract

This work is the initial stage of the development of an online flow monitoring system for the resin impregnation phase of the Resin Transfer Moulding process. Online monitoring of the process is proposed to provide an estimation of the component's state and to predict the defects, such as voids and dry spots. This paper analyses a dielectric sensor, which integrates to the process and measures the change in the impedance. The main contribution to the changes in the sensor response comes from the resin arrival on to the sensor during the impregnation phase. The proposed sensor consists of two parallel line electrodes embedded in an insulator. The design optimization is performed by analysing and modelling the geometry and the materials of the sensor. In addition, the developed monitoring system involves pressure transducers which measure the composite material state during the infusion phase. The pressure sensors operate as indicators of resin's state and they are used for the process monitoring. This information will be used for the development of an algorithm for the resin frontal flow and enhance the insight of the flow defects mechanism.

1. Introduction

The RTM process is one of the most promising and cost-effective technologies used for production of large complex three-dimensional composite components [1, 2]. The RTM process is mostly used in aeronautical, automotive and wind energy applications, such as the manufacturing of fuselage, wing-spars and wind turbine blades. The process ensures the reduction of mass and the increase of operating life without compromising on the high performance of the aimed design. The main steps of the RTM process for the manufacture of a simple part are the preform preparation, the draping of the preform inside the mould cavity, the closing of the mould, the resin injection and finally the curing phase.

The manufacturing techniques that are used for composite materials and the variability of the materials introduce faults during the manufacturing process. Numerical simulations are useful process design tools when accurate parameters' data are used to describe the problem [3]. However, the collection of the parameters that are used by these models is lacking and for that reason, online monitoring of the process is suggested to enhance the understanding of resin's flow and cure. The monitoring system is an essential stage to enhance the process accuracy. A monitoring system can be utilized either for active control of the process parameters, such as the resin flow or to evaluate the quality of a complete injection [4, 5].

The multivariable character of materials, conditions and geometries add challenges to monitoring and predicting the behaviour of the process. The main interest is focused on the determination of voids, dry spots and porosity which are influenced by the resin's flow and viscosity and the degree of cure [6]. Dielectric analysis (DEA) and ultrasonic techniques are utilised to collect information on the state of the resin [7]. However, due to control issues with ultrasonic techniques, the DEA appears to be the most promising and popular method for monitoring the resin state in composite materials manufacturing [8].

This paper describes the design approach for the development of a flow monitoring system and the dielectric sensors which will be used for flow monitoring. The primary objective of the study is to measure the resin flow during the injection phase of the RTM process. In this report the preliminary tests for the flow and pressure measurement with the Vacuum Infusion (VI) process are presented. The design methodology of the selected dielectric sensor is described. Also, the monitoring system with the piezoelectric pressure transducers which are embedded on the RTM tool is presented. Figure 1 shows the L-Shape mould, which was used for the development of the flow monitoring system and the integration of both pressure and dielectric sensors.

Figure 1. Integration of pressure transducers and dielectric sensors on an L-Shape Mould.

2. Design approach

2.1. Dielectric sensor analysis

In order to measure the frontal flow of the resin with dielectric sensors, the DEA methodology was selected. An alternating sinusoidal excitation voltage is applied to the drive electrode and the changes are detected by the sensing electrode. The main contribution to the changes in the sensor response comes from the resin coverage of sensor's surface. Then, the sensor signal is correlated to the resin location [9] which provides information on the frontal flow position.

The impedance of the sensor is important for understanding the measured changes and this facilitates the correlation function with the frontal flow. Figure 2 illustrates the proposed model for the equivalent impedance calculation of the selected sensor and the geometry of the sensor. The sensor consists of three electrodes which are embedded in a Polyethylene terephthalate (PET) insulator. The method uses the dielectric Maxwell model, which is the resistive and capacitive (RC) equivalent of a dielectric material [10]. The geometry of the sensor is divided in sections and the material properties (dielectric permittivity and resistivity) were taken into consideration for each element (Figure 2.a). The current method uses a simplified equivalent circuit of the sensor. It excludes the stray capacitances and the fringing electric field effects [11]. The impedance for each section is calculated with regards to the location of the electrodes and the surrounding materials. The changes in the impedance is modelled with a function impedance (Z_x) which includes the properties of the materials under test (MUT). This was used for the equivalent sensor impedance calculation and the analysis of the changes due to resin impregnation.

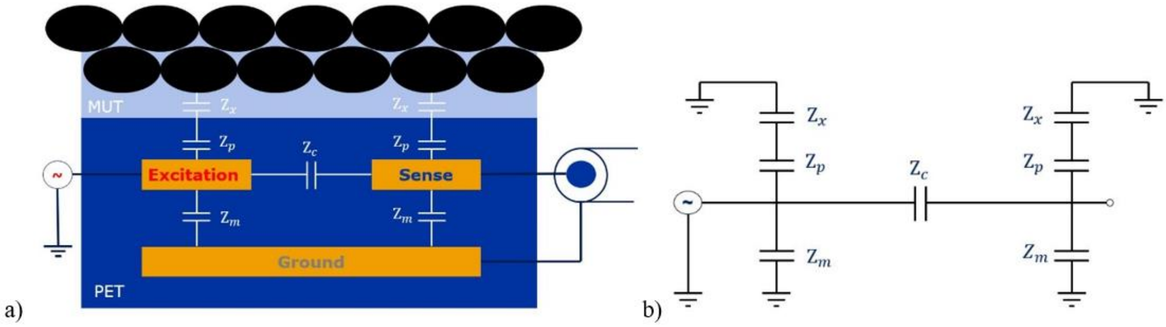

Figure 2. a) The geometry of the sensor with the electrical elements, which are used for the analysis and b) the equivalent circuit with regards the proposed model.

The modelling of the sensor enhances the understanding of the electric field response due to differences in each material's conductivity. The electrostatic behaviour of the proposed sensor has been analysed. The Partial Differential Equations (PDE) toolbox in the MATLAB software was used for the electrostatic analysis, which can be used to solve electrostatic field equations. The equations used for the analysis are as follows.

$$\nabla \cdot \vec{\boldsymbol{D}} = -\rho_v \overset{\vec{\boldsymbol{D}}=\varepsilon\cdot\vec{\boldsymbol{E}}}{\Longrightarrow} \nabla \cdot \left(\varepsilon \cdot \vec{\boldsymbol{E}}\right) = -\rho_v \tag{1}$$
$$\vec{\boldsymbol{E}} = -\nabla V \tag{2}$$

where, ε is the coefficient of dielectricity, ρ_v is the space charge density, V is the scalar potential, $\vec{E}$ is the vector of the electric field and $\vec{D}$ is the electric displacement field.
The boundary conditions were applied onto the curves of the electrodes and the materials, where the areas of interest are located. In this case study, the grounded areas have zero potential. The electrode to which voltage is applied has a potential equal to 1 *Volts*. Dirichlet is the selected boundary condition because of the known variable, which is the potential of the driving electrode. Table 1 includes the dielectric coefficients used in the model and the domains of each material.

Table 1. Dielectric coefficients of the materials used for the electrostatic study [12].

Material Name	*Dielectric Coefficient*	*Domain*
Copper	0	A
PET	2.1	B
Air	1.00059	C
Epoxy resin	3.6	C
Carbon fibers	0	D

2.2. Pressure transducers

In this study, the pressure sensors were used for the process monitoring. Among the process monitoring techniques, pressure transducers have the following advantages; (a) they are embedded in the process without affecting the final manufactured parts; (b) they are applicable with the RTM process, regardless the materials and process conditions; (c) they are robust to noise (high Signal to Noise Ratio) and have fast response [4]. On the other hand, they can provide local information. Thus, the implementation of a monitor system with sufficient number of sensors to cover a large cavity area turns into a complex and expensive system [13].

The resin flow in fibre materials can be described as the flow of a liquid in porous media and is given by Darcy's law as follows.

$$\bar{\boldsymbol{v}} = -\frac{\bar{\boldsymbol{K}}}{\eta} \cdot \Delta \boldsymbol{p} \tag{3}$$

where $\bar{v}$ is the volume averaged velocity, $\bar{K}$ the permeability tensor of the porous media, η the resin viscosity, and p the fluid pressure. The solution of the Equation (3) can provide the flow speed when the fluid's pressure field inside the cavity is known. The measurement of the pressure during the process could aid on understanding any flow disturbancies which lead to the creation of defects and are related to the resin flow.
The sensors are placed at the inlet and outlet ports of the L-Shape mould as shown in Figure 3, and provide local pressure values, which are presented in the next section.

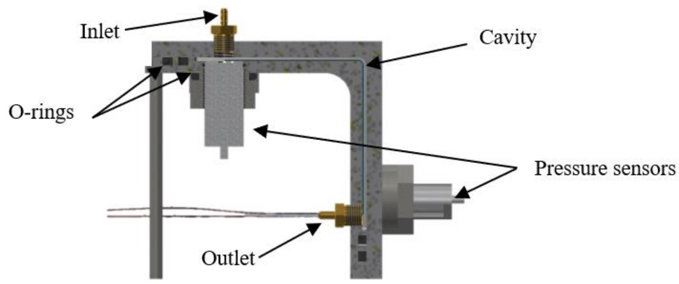

Figure 3. 3D CAD of the pressure transducer and the L-Shape mould.

3. Results

3.1. Sensor modelling

The main variables for the modelling of the sensor response are the dielectric thickness of sensor's insulator and the distance between the electrodes. The distance between the electrodes is correlated to the thickness of the measuring material, which in this case study is the impregnated carbon fibre fabric. The simulation includes two case studies, which are linked to the presence or not of resin. A sensitivity analysis of the voltage drop on the sensing electrode was carried out and that was one of the criteria for the selection of sensor's final geometry. It can be observed that the sensitivity of the sensor is increased with the addition of a dielectric layer between the electrodes and the MUT. Figure 4 presents the sensitivity analysis and the voltage drop when resin is the MUT with regards to the electrodes' distance.
The accuracy of the sensor is defined as the percentage of the response when a material is detected on the sensing electrode. For the case studies, the accuracy of the sensor was calculated with the following equation.

$$s = \frac{V_{resin} - V_{air}}{V_{resin}} \cdot 100\% \tag{4}$$

where V_{resin} is the potential of the sensing electrode for the case study of resin and accordingly V_{air} when air is on the top of the sensor.

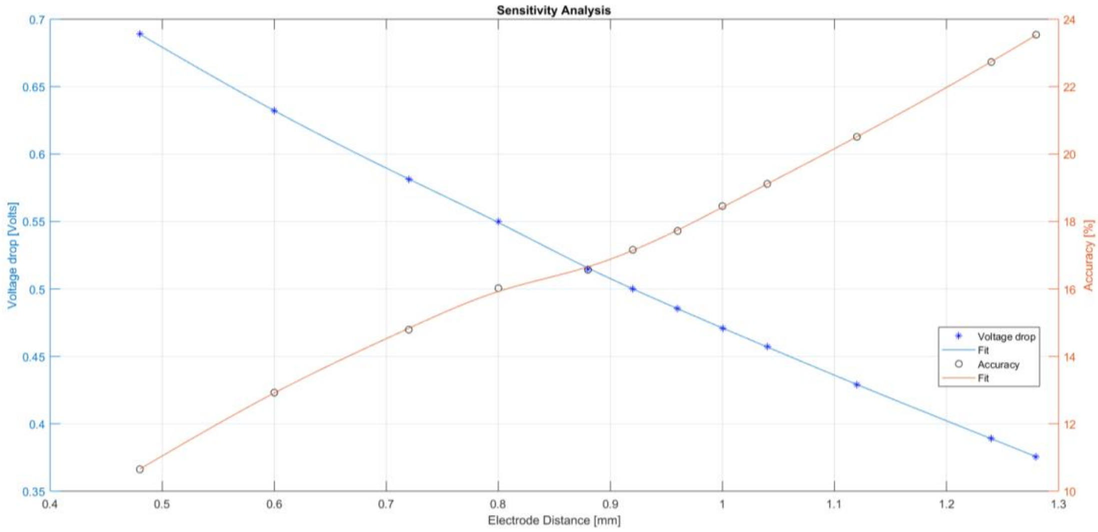

Figure 4. The accuracy and voltage drop of the sensor as a function of electrodes distance.

The voltage of the electrodes for the case studies was calculated with the PDE toolbox of MATLAB. Figure 5 presents the selected geometry of the sensor and the results of the modelling. The designed sensor is 4 *mm* wide and the overall thickness is 0.5 *mm*. Figure 5.a illustrates a 2D section of the sensor geometry and its domains (Table 1), which are used for the simulation. Figure 5.b shows the voltage distribution of the selected sensor. The voltage across the sensing electrode is 0.52 *Volts*. Also, as expected the electric field is interrupted at the level of the carbon fibre tows, because of the conductivity of the carbon fibre. This is an inevitable limitation with the carbon fibre. Thus, the sensitivity of sensor is crucial for detecting the resin impregnation.

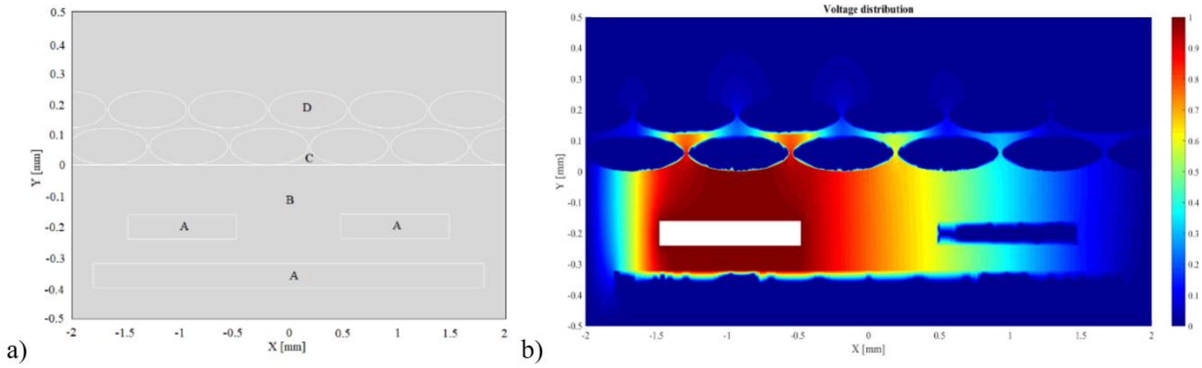

Figure 5. a) The geometry of the sensor with the domains for the simulation (Table 1) and b) the voltage distribution.

3.2. Pressure measurements

The initial test for the process monitoring with pressure transducers is presented in this paragraph. The pressure sensors were embedded on the wall of the mould to monitor the pressure gradient changes during the resin impregnation phase of a glass fabric reinforcement. The materials used for the measurement are an unidirectional (UD) glass fabric and the Gurit epoxy resin Ampreg 22 with the slow hardener. The experimental sensing system includes two absolute pressure sensors by Composites Integration Ltd, which were flashed to the cavity wall, and the NI9205 data acquisition system by National Instruments.

In this study the outlet of the L-Shape mould was attached to a vacuum pump and the inlet was connected with the resin pot. The resin's state is at the ambient pressure and temperature. Figure 6 presents the measured pressure inside the cavity of the mould at the inlet and outlet ports during the infusion time. The illustrated results indicate that the infusion inside the cavity begins when the pressure sensor at the inlet detects the resin and the pressure increases from 0 bars. During the infusion, the inlet sensor measures the local pressure gradient alterations and provides information on the material's state. The resin arrives at the outlet port and the infusion ends when both sensors soar to ambient pressure.

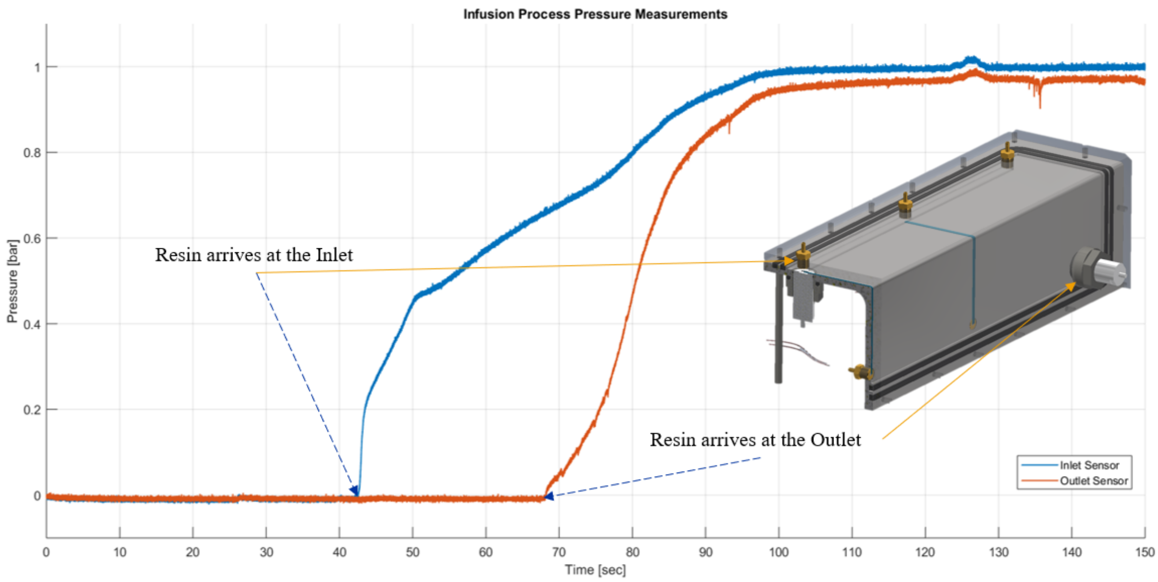

Figure 6. Inlet and outlet pressure measurements of the mould's cavity during VARI process.

4. Conclusions

The proposed sensor was modelled using the PDE tool in MATLAB. Electrostatic analysis can provide information of the sensor response, which is used during the design process of the sensor. The materials properties were considered during the design and the simulation of the sensor. The modelling aids on optimizing the geometry and enhances the sensitivity of the sensor. This information will be used for the impedance analysis and validation of the flow monitoring system.
The pressure transducers can provide information on both the physical changes of fluid's pressure and the arrival of the resin at their certain point [13]. This is an advantage compared with other local sensor systems, such as thermocouples, interdigital capacitive sensors and point-voltage sensors [14]. The development of an algorithm based on Darcy's law (Equation 3) is the next stage of this study. The algorithm will be updated with the real-time measurements of mould pressure by the embedded pressure sensors and it will be combined with the signal provided by the dielectric sensors.
Online monitoring of the process is proposed to provide an indication of the component's state and to predict defects. The real-time information of composite's pressure gradient changes could potentially reduce the defects related with resin flow during the process. This reduction can be succeeded either by modifying the process parameters on the designing phase or by actively controlling the pressure during the process. Consecutively, the improvement of the part's quality reduces the wastage products and the production costs.

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