STUDY OF RESIN TRANSFER MOULDING PROCESS PARAMETERS FOR THE MANUFACTURING OF THE SENSOR NOSE CONE

by

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ABSTRACT

Reducing void content in components produced via Resin Transfer Moulding (RTM) is one of the challenges for improving the surface quality achieved with this manufacturing process. This thesis is an attempt to understand the impact of RTM process parameters vacuum assistance, injection pressure and hydrostatic pressure, in the void content and in the surface quality of the laminate. To perform this study it was devised a strategy that consisted in two iterative stage processes, which were intercalated by an intermediate learning process. The first stage consisted in defining and implementing an initial hypothesis for the Sensor Nose Cone, based on information collected from the reviewed literature. Afterwards, the intermediate learning process was planned based on a factorial design at two levels, which allowed to analyse behavioural trends caused by changes in the process parameters. At last, the second stage consisted in defining and implementing a hypothesis based on the results of the intermediate learning process.

The results obtained in this study showed that using a combination of a low injection pressure value combined with a high hydrostatic pressure have contributed to a better surface quality of the Sensor Nose Cone. Additionally, despite the use of vacuum assistance did not have shown a positive influence for the Sensor Nose Cone surface quality, it provided benefits when applied to flat panels in the designed experiments. It was concluded that this may have been due to the fact that the designed experiments did not represent the true state of nature for the Sensor Nose Cone scenario.

Key words: resin transfer moulding; vacuum assistance; injection pressure; hydrostatic pressure; voids in composite laminates; surface quality in composite laminates.

PREFACE

This Master Thesis report was submitted as part of the forth semester program of the Cand.polyt. Manufacturing Technology at Aalborg University. The project period ran from 01/02/2016 to 01/06/2016. A reading guide for this report is provided on page V. This project was proposed and developed in partnership with Terma Aerostructures A/S, which also provided all the material resources and equipment for making the tests.

READING GUIDE

This thesis is organized in six chapters and in three appendices, and its content is resumed below:

Chapter 1. Introduction: in this chapter is made an introduction to the project, presenting its context, the statement of the problem, the purpose of the study and the primary research question. The chapter concludes with the description of the assumptions, limitations and the scope for the project.

Chapter 2. Literature Review: in the literature review it is provided an introduction to voids followed by an analysis to the effects of each process parameter studied in this project; respectively vacuum assistance, injection pressure, and hydrostatic pressure, based on the literature findings. Finally, it is made a summary with all the conclusions taken from the sections included in this chapter.

Chapter 3. Approach and Method: this chapter starts with an explanation about the iterative learning process used in the present study. Then, it is presented the approach the approach and the methods, which are part of the strategy defined for the project. The chapter finishes with concluding remarks about the strategy defined.

Chapter 4. Implementation: this chapter covers the implementation of the initial hypothesis and of the designed experiments for the intermediate learning process, and it ends with a conclusion about the challenges of implementing each task

Chapter 5. Results: this chapter is composed by three sections that present the results from each experiment and by a forth section that discusses the conclusions made. In Section 5.1 and 5.2, are presented respectively the results of the initial hypothesis and the results of the designed experiments for the intermediate learning process. Section 5.3, starts by giving an insight on the implementation of the second hypothesis and afterwards are presented the results achieved. The chapters ends in Section 5.4, with the conclusions from each set of results.

Chapter 6. Concluding Remarks: this chapter contains an overall conclusion for the report, as well as perspectives and thoughts for future works that are presented in Section 6.2.

Appendix A. Permeability Test: this appendix contains the description of the procedure taken to determine an approximate value of the permeability of the Sensor Nose Cone laminate. It includes the method chosen, the results obtained and their final discussion.

Appendix B. Determination of Injection Time: this appendix contains the description of the procedures taken to simulate and determine the injection time for the Sensor Nose Cone. It includes the method chosen, the results obtained and their final discussion.

Appendix C. Designed Experiments Based on Factorial Design at Two Levels: this appendix contains the description of the procedures made in the intermediate data collection stage, as well as the results obtained and their discussion.

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This accomplishment would not have been possible without all of you.

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CHAPTER 1. INTRODUCTION

1.1. INTRODUCTION

In the past years, several manufacturing companies in the field of composite structures have shown an increased interest about Resin Transfer Moulding (RTM) processes. Respectively, each company that decides to invest in RTM does it with its own expectations, convictions and experience. Despite that, most companies investing in RTM do not possess the knowledge and experience about closed moulding of composites, and many raise the questions towards what is happening inside the mould cavity.

As one of the interested companies, Terma Aerostructures A/S has decided to invest in studying the RTM process with the goal of increasing the understanding about the process parameters as well as developing a baseline for a robust manufacturing process. By doing so, it will increase the company capabilities, allowing Terma Aerostructures A/S to apply this manufacturing process to future products.

1.2. CONTEXT

The present project is a continuation of the work performed during the third semester of the Master of Manufacturing Technology [1]. The motivation of the previous project was to develop a RTM process to replace the current production processes for the Sensor Nose Cone, with the goal of reducing production costs.

As can be seen in Figure 1, the Sensor Nose Cone is an assembly composed by four parts: the bulkhead, the skin, the sensor mount and the nose. The skin is manufactured by metal spinning an aluminium sheet and then machined to its final shape. The sensor mount, bulkhead and nose are machined from aluminium billets. Before being assembled together, the parts undergo a series of quality controls, surface treatments and paint jobs. Once all the preparations are completed, the parts are assembled together and afterwards the gaps of the assembly joints are sealed using a polyurethane joint sealant. Finally, the surfaces are polished to level all the irregularities in the joints, and the Sensor Nose Cone is painted. By analysing the Sensor Nose Cone production, it was concluded that having an assembly composed by four main components results in higher workload due to the number of tasks and processes that need to be carried out, and it also results in a higher consumption of material resources. Therefore, the problems with the current Sensor Nose Cone design are related with quantity of processes needed to produce a single unit, which lead to long production time and high costs involved.

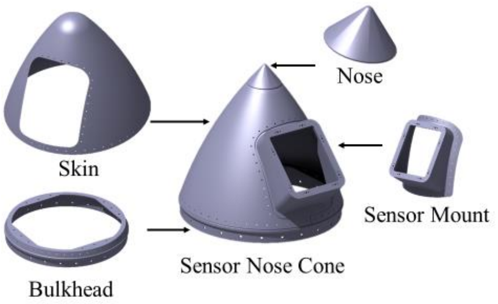

Figure 1 - Sensor Nose Cone main components and assembly configuration

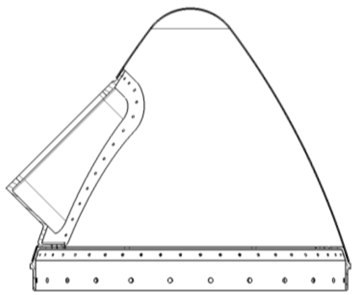

Figure 2 - Cross section view of the Sensor Nose Cone

Based on those issues, Terma Aerostructures A/S proposed a research project to evaluate the possibility of converting the current aluminium design to a composite structure, manufactured via RTM, to achieve significant cost savings. The redesign of the Sensor Nose Cone would require producing the skin, sensor mount and bulkhead in a single component, thus resulting in substantial reduction of the production processes.

In order to implement a RTM process, several changes were made to the initial geometry of the Sensor Nose Cone, see Figure 2, while the mechanical properties of the component were maintained. The resultant redesign can be seen in Figure 3. In regards to its structure, the composite version of the Sensor Nose Cone uses an 11 inch +/- 45 degrees fibreglass biaxial sleeve as the reinforcement material with an epoxy matrix constituted by Araldite® LY 1564 and by Aradur® 3486 as the hardener. In Figure 4 it is illustrated the lay-up sequence, in which can be seen three layers of reinforcement material used for the skin, marked in red, and eight layers marked in green, used to reinforce the joggle area which will be prone to bolt shear loads. It should be noted here for future references that, the lay-up can be divided in four sections based on the number of layers stacked in each section, which are also represented in Figure 4. The first section is constituted by only the three skin layers that cover the entire mould cavity. Then, the second section, also referenced as the tapered section, is a transition region in which the reinforcement layers for joggle start to appear. Due to the change in the number of layers between the first and third sections, the second section will have a resin rich area. The third section is made of eleven layers, three from the skin and another additional eight layers to reinforce the joggle area. Finally is the forth section, although this section has the same number of layers as the previous one, it has additionally a fibreglass rod passing in the middle of the reinforcement layers of the joggle. The purpose of the fibreglass rod is exclusively to hold the eight reinforcement layers, preventing them from falling inside the mould cavity while the mould is being closed. Like the second region, the forth has also has a resin rich area close to the vent ports.

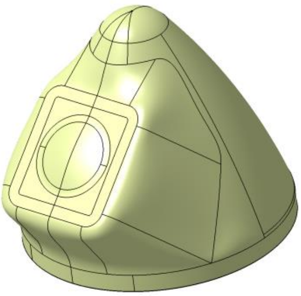

Figure 3 - Shape of the redesigned Sensor Nose Cone

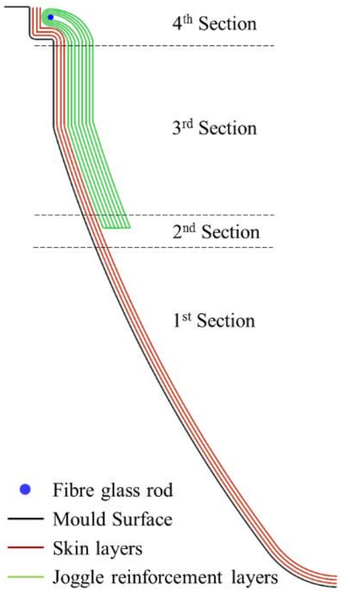

Figure 4 - Cross section of the lay-up

In the previous project [1], it was also developed and prepared the tooling and equipment necessary to implement the RTM process for the Sensor Nose Cone. In Figure 5, is shown the O-ring used to seal the mould cavity, which was produced by using an O-ring cord that was cut with the length of seal grove, and then the ends were bonded together using cyanoacrylate glue. Figure 6 shows the O-ring mounted on one of the sides of the concave mould, while in Figure 7 is captured the moment before closing the mould, in which both sides are bolted together and the convex side of the mould is ready to be inserted. Lastly, in Figure 8 is shown the set-up with the equipment for the production of the Sensor Nose Cone. In the centre of

Figure 8 is the temperature control unit and behind it is the Sensor Nose Cone mould. On the left side is the resin catch pot used as a container for the excess resin that comes out of the outlet ports, and on the right is the pressure pot used to inject the resin.

Figure 5 - O-ring seal

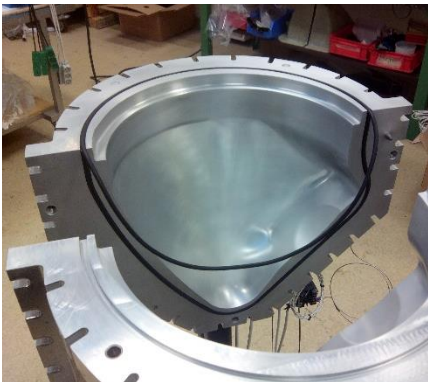

Figure 6 - O-ring mounted on the groves of the open mould

Figure 7 – Sensor Nose Cone mould ready to be closed

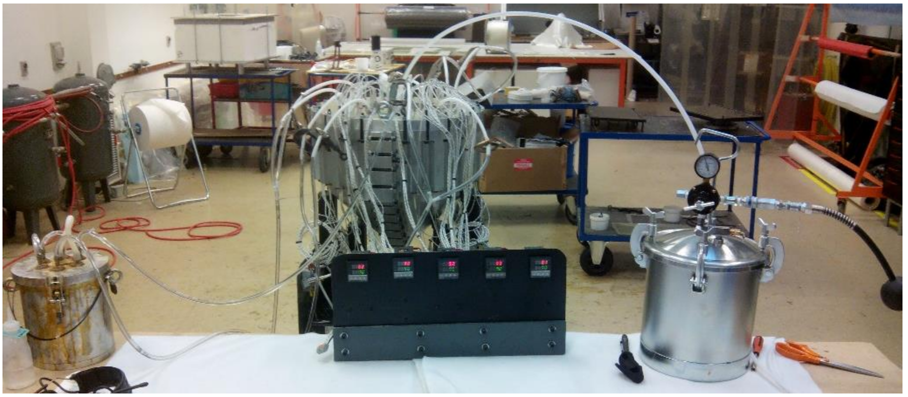

Figure 8 – Set up for the manufacturing of the Sensor Nose Cone

At the end of the previous project, [1], it was concluded that producing a part via RTM with a smooth surface free of voids would lead to additional cost savings, due to the reduced workload to prepare the surface before painting. Therefore, it was decided to continue studying the potential of the RTM process for applications such as the Sensor Nose Cone, with the purpose of analysing the impact of RTM process parameters to reduce the presence of voids in the surface of the part.

1.3. STATEMENT OF THE PROBLEM

In some cases, parts produced via RTM have surface irregularities caused by residual curing stresses and also voids, which can be caused by the entrapment of air or by poor wet out of the fibres. In such occasions, the poor surface quality of the part achieved with RTM requires additional processes to smoothen and even out then surface, before being painted.

As a manufacturer, Terma Aerostructures A/S is concerned in removing completely the presence of voids in the surface of the part, for components produced via RTM. By doing so, it is pretended to improve the surface quality of the laminate, thus reducing the workload to prepare the surfaces to be painted.

1.4. PURPOSE OF THE STUDY

The study here presented is focused in analysing the consequences and impact of RTM process parameters with the goal of reducing the presence of voids in the surface of the part. More specifically, the impact of injection pressure, vacuum assistance during injection and the use of hydrostatic pressure during the curing stage. Figure 9 illustrates the main steps of a RTM process, and highlights the steps in which the study is focused on.

Figure 9 – Main steps of RTM process

1.5. SIGNIFICANCE OF THE STUDY

It is the interest of all manufacturing companies that use RTM, to make the process as efficient as possible. In this specific case, by improving the surface quality after the RTM process, it will result in cost savings in additional surface treatments.

Additionally, companies are also interested in reducing void content, because besides affecting the surface finish, it also affects the mechanical properties of the composite laminate. Therefore, having a part with a void free surface can be associated with better mechanical properties of the laminate.

The analysis of RTM process parameters also contributes to an increased knowledge and experience based on a real application of the studied concepts, and will allow Terma Aerostructures A/S to approach RTM processes with confidence on its advantages, by being a reliable and repeatable process capable of producing quality parts.

1.6. PRIMARY RESEARCH QUESTION

The analysis performed in this study is focused in answering questions regarding the impact of RTM process parameters, such as injection pressure, vacuum assistance during injection and hydrostatic pressure during curing, in the quality of the surface finish of a Sensor Nose Cone.

Based on the conclusions derived from the experiments, this study attempts to define an ideal approach to inject and cure parts manufactured via RTM.

1.7. ASSUMPTIONS LIMITATIONS AND SCOPE

In the development of this project it is assumed that the composite version of the Sensor Nose Cone, developed in the previous semester, can be used as an example for future applications.

Regarding tooling and equipment, it is considered that the necessary devices to control the process parameters were available, could be used without limitations and were free of defects.

In what concerns the variations of the conditions in the room environment in which the experiments were performed, these were considered negligible. Therefore, it is assumed that the environmental conditions of the room cannot be used as an argument to justify two different results from experiments.

This study was limited on analysing three RTM process parameters, these being: injection pressure, vacuum assistance during injection and hydrostatic pressure during curing. Therefore, it is necessary to acknowledge that there are other parameters capable of affecting the void content in the surface of a part, which were not taken into consideration, such as: surface finish of the mould cavity, the method to clean and release the mould, fibre arrangement, and fibre volume fraction.

The focus of the study is within the injection and curing stages of the RTM process. Regarding the scope of the conclusions, these shall only be applied to cases that have the same amount of control of the process parameters as in this study.

CHAPTER 2. LITERATURE REVIEW

In this chapter is made a literature review of three RTM process parameters: vacuum assistance, injection pressure and hydrostatic pressure. Moreover, their impact on void formation and growth is highlighted. Each process parameter is presented independently from the others parameters, in its own separate section. In this review is also given an overview of the results and conclusions gathered from other studies that were considered relevant to the present topic. Thereby an initial understanding of the process parameters is achieved and may be used to design a RTM test campaign.

2.1. INTRODUCTION TO VOIDS

Although the terms void and porosity have not been yet defined by the composite industry, it is necessary to establish a definition for both terms. In this study, the term porosity is used to refer a small pore, whereas void implies a large pore.

The reduction or elimination of voids in components produced via RTM requires understanding the mechanics of void formation and growth during injection and curing of the laminate. Mentioning Hamidi *et al.* [2], there are two sources of voids formation in a RTM process: 1) mechanical entrapment during mould injection; and 2) vaporization of volatiles.

The mechanical entrapment of voids is assumed to arise due to constant changes in the flow path of the resin caused by the anisotropic permeability of the reinforcement material [2]. In composites, the anisotropic permeability generates two types of flow in the preform. One being classified as a viscous flow, in which the matrix travels through the weave openings in between fibre bundles, and the other being caused by capillary flow, in which the resin flows in the tows of the fibre bundles. Considering the separate effects of each type of flow during the preform impregnation, a viscous flow occurs with higher injection flow rates, resulting in the entrapment of voids within the fibre bundles. On the other hand, capillary flow occurs at lower flow rates and it leads to the entrapment of voids between fibre bundles.

Another effect of the velocity is related with the flow pattern of the matrix flow. As it is thought, with a high flow speed, the resin passes through the fibres and causes the formation of vortexes, thus leaving dry surfaces on the fibres.

In what concerns the formation of voids due to vaporization of volatiles, it is believed to be related with hygroscopic water absorption by the reinforcement and matrix materials. As documented by Campbell [3], even with small amounts of moisture, during the injection and curing process the conditions can lead to the evaporation of water inside the laminate, resulting in large gas volumes and pressures.

For the purpose of this study, mathematical methods for the prediction of void formation and growth were not used, because as referenced by Hamidi *et al.* [2], even though several models were created, such models can only be applied to special conditions that replicate the ones in which they were created. Based on that, it was chosen not to do so since it would reduce the applicability of the results obtained in this project in real conditions of production.

2.2. EFFECT OF VACUUM ASSISTANCE

In composite manufacturing, it is a common practice to use vacuum in order to improve the quality of the laminate. As explained by Hayward *et al.* [4], the positive effect of vacuum assistance is significant, since the resin flow efficiency is improved due to the increased pressure gradient, as well as due to the removal of moisture and contaminants absorbed while handling the materials. Lundstrom *et al.* [5], also indicates that the improved quality associated with the use of vacuum is mostly caused by the mechanical effect due to a reduction in pressure in the trapped air that enhances the degree of penetration of the resin.

On the other hand, with the use of vacuum assistance some problems can arise. These can be caused by: an improperly sealed mould, an incomplete degassing of the resin matrix and the increased size of the voids due to the reduction of pressure. When using vacuum with an improperly sealed tool, it generates airflow from the outside of the mould to the inside, in the direction of the vent ports. This airflow consequently creates a stream of voids in the laminate, which due to the constant leak flow during injection, will be entrapped as the resin gelation point is reached, due to the constant leak flow during injection. In a situation using a resin system that was not entirely degassed, it can result in a degassing process while the resin is being injected, leading to an increased quantity of voids in the laminate. Finally, due to the pressure drop the existing voids will expand, thus making it harder to remove them, because of the increased adhesion forces with the reinforcement, which makes them less mobile. While smaller voids have lower adhesion forces which makes them more mobile.

2.3. EFFECT OF INJECTION PRESSURE

In most applications, the use of vacuum is enough to create the necessary pressure gradient for the resin to fill the mould cavity, but with the purpose of increasing RTM process efficiency, most manufacturers are using pressurized resin pots to increase even more the pressure gradient, thus increasing the injection flow rate. As explained in the beginning of this chapter, due to the anisotropic permeability of the lay-up, the permeability inside the fibre bundles is considerably lower than between weave openings resulting in two different types of flow paths.

As a result of the lower permeability inside the fibre bundles, when the matrix flow speed increases, viscous flow takes place. This means that the resin will predominantly flow around the fibre bundles causing the entrapment of air in the fibre bundles.

2.4. EFFECT OF HYDROSTATIC PRESSURE

In additive polymerization materials [6], as is the case of epoxies, void formation and growth is largely caused by entrapped volatiles [3]. In this type of systems, the main volatile is considered to be originated from hygroscopic water absorption by the reinforcement material and matrix. As explained by Campbell *et al.* [3], the amount of absorbed moisture from the atmosphere is dependent on the relative humidity of the surrounding environment, whereas the absorption rate is influenced by the room temperature. For those reasons, composite manufacturers invest in technology to control the atmospheric conditions for the rooms in which composite lay-up are made.

The entrapped water develops into a void when the process conditions lead to the evaporation of the volatiles. Void growth occurs if the volatile pressure exceeds the resin pressure, therefore the combined quantity of absorbed moisture, in both reinforcement and matrix, determines the resultant vapour pressure generated during the curing cycle. Having a higher moisture content and process temperatures results in a higher vapour pressure that increases the propensity for void formation and growth.

For that reason, having a higher hydrostatic resin pressure than volatile pressure is essential to keep the volatiles dissolved in solution and the necessary hydrostatic pressure can be determined using the saturated water vapour pressure as a reference value. It is possible to use this method with the graph shown in Figure 10 and determine the minimum hydrostatic resin pressure necessary to keep the volatiles in solution, by intercepting a vertical line at the curing temperature with the saturated water vapour line, marked in blue.

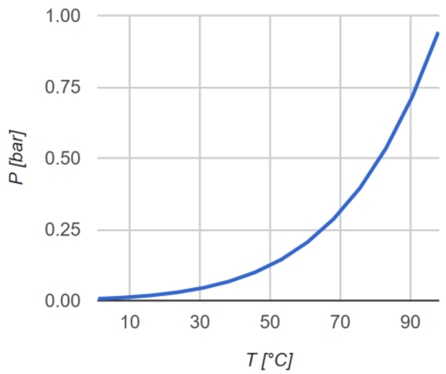

Figure 10 – Graph of saturated water vapour pressure [7]

Due to the simplicity of this approach, it is necessary to acknowledge that in the case of existing other types of volatiles, that could have different vapour pressure than the water, it would increase the complexity of defining the appropriate hydrostatic pressure to apply.

2.5. CONCLUSIONS

The studied literature provided an essential understanding about the three process parameters considered in this project. While analysing the conclusions from different studies, it became evident that each author made similar conclusions. Such evidence is important because it gives confidence about the conclusions made and, making possible to use them as references for the development of this project.

Thereby, Table 1 was constructed based on the conclusions made by Lundstrom *et al.* [5], and it describes how the increase of each of the process parameters can influence void content. In the same table, the plus and minus signs represent correspondently an increase and decrease of the value of the parameters.

Table 1 – Influence from process parameters, based on [5]

Parameter	**Type of Change of the parameter**	**Void Content**
Vacuum Level	+	-
Injection Pressure	+	+
Hydrostatic Pressure	+	-

From the literature, it was also possible to establish several good practices to be used when working RTM composite parts, which were divided in two different groups. The first group is not directly related with the RTM process, but plays an important role to obtain a void free laminate. Within this first group are the following considerations:

- Leak free mould: if vacuum is used, a leak in the sealant will create an air stream, leading to the appearance of voids in the direction from the leak to the vent ports.
- Complete matrix degassing: when using vacuum, if the resin matrix is not properly degassed, the negative pressure gradient inside the mould cavity will generate the conditions for a degassing. This will facilitate the release of entrapped air and volatiles that can cause voids.
- Controlled environment: the room conditions can influence the laminate quality. Having clean storage and working room, free of impurities and with a low relative humidity, will result in a laminate with lower content of contaminants.

Additionally it was also possible to conclude that in situations in which the mould has a leak or the resin matrix has not been completely degassed, it is recommended not to use vacuum and, instead of that, use pressure at the injection pot to push the matrix inside the mould cavity. However, this approach requires a double sided mould, which results in an increase of investment for their manufacture when comparing with a Vacuum Assisted RTM (VARTM) process.

The second group of good practices is directly related with RTM process, during the injection and curing stages. The injection stage of the RTM process, as illustrated in Figure 9, can be separated in five sub stages, as shown in Figure 11.

Figure 11 – Sub stages of RTM injection stage

The first two sub stages are relative to the creation of a vacuum pressure in order to evacuate air and other volatiles from the inside of the mould cavity. Once the specified vacuum pressure is reached the injection port is opened to let the resin flow. As explained in Section 2.3, the matrix flow speed should be as low as possible in order to avoid a predominant viscous flow, which results in the entrapment of air inside the fibre bundles, but it should be fast enough so that the injection process is completed before the resin reaches the gel point. The fourth sub stage corresponds to the complete filling of the mould cavity, which is considered to be completed when a clear stream of resin flows out from the vent port. Once the mould filling is completed the vent ports can be closed.

After closing the vent port, the curing stage can be initiated. For better quality of the laminate, as presented by Campbell *et al.* [3], the resin matrix should cure while applying a hydrostatic resin pressure in order to keep the volatiles in solution. In cases which the necessary hydrostatic pressure is unclear, it is possible to define it by using the saturate water vapour pressure as a reference for the curing temperature. The hydrostatic pressure should be created after closing the vent port, and before the resin reaches the gel point, but maintained until the laminate curing is completed.

Finally, the conclusions made based on previous studies about the three RTM process parameters, will allow comparing and discussing the results obtained from the test trials made in this study.

CHAPTER 3. APPROACH AND METHOD

The purpose of this chapter is to delineate and present the strategy specially designed to study the influence of three variables in the surface finish of a part produced via RTM process. The chapter takes off with an explanation about the iterative learning process, followed by a description of the devised approach and method for this study. The chapter finishes with concluding remarks about the strategy made.

3.1. LEARNING BY ITERATION

As explained by Hunter *et al.* [8], scientific research is characterized by being a process of guided learning, in which learning is considered to be an iterative process. In other words, a scientific research is a guided iterative process which evolves based on the knowledge obtained from each iteration. As illustrated in Figure 12, the learning process starts with an initial hypothesis based on assumptions created in a deduction process, which makes predictions about certain consequences that can then be compared with test results.

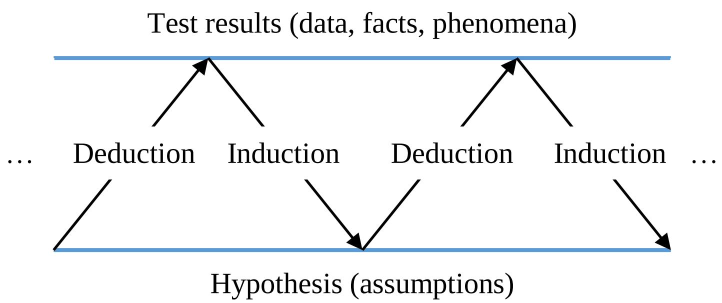

Figure 12 – The iterative way of learning [8]

In situations in which the results obtained do not match the expected ones from the hypothesis, those differences can then be used to adjust the previous hypothesis by an induction process. Thus, a second iterative cycle can start with the new improved hypothesis, being the goal of each iteration to keep on learning and improving the hypothesis, based on the knowledge gained from each experiment.

As illustrated in Figure 13, a feedback loop can also be used to describe the iterative process of learning. When performing experiments, the hypothesis shall only be changed based on information collected from the results of the true state of nature experiments. Thus, it should be noted that to this project, the expression true state of nature experiment is used to define an experiment that replicates the same conditions of a real case.

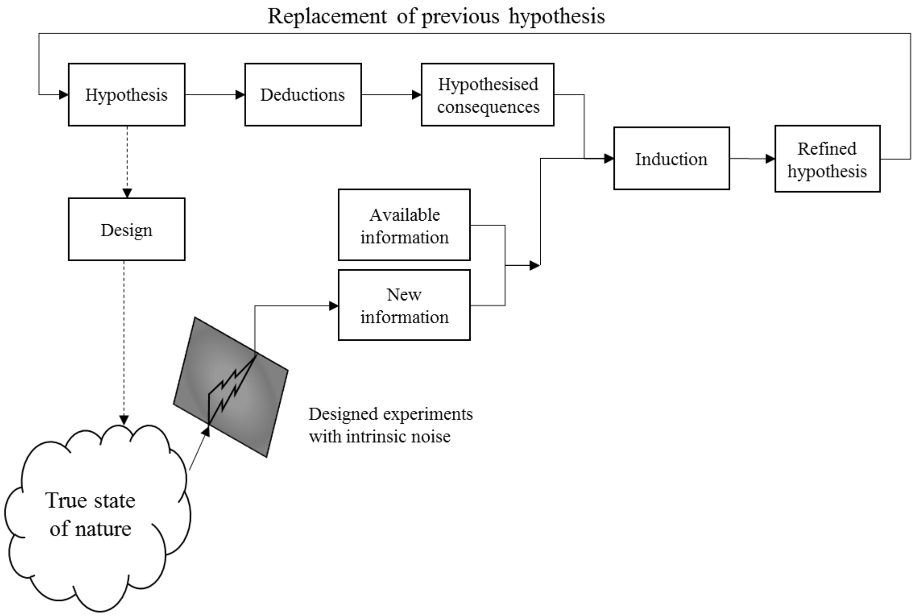

Figure 13 - Representation of the iterative learning process using a feedback loop [8]

It should be noted that to execute experiments it is not necessary to have a defined strategy, although this might lead to an inefficient iterative process, whereas without knowledge about the subject it is impossible to learn and to improve. Hence, the goal of using statistical methods is to make the process as efficient as possible. Finally, the true state of nature has to be correctly replicated in order to extract the pretended data from the experiments, otherwise they will provide results with useless applicability.

3.2. APPROACH

As explained in Chapter 1, Sections 1.4 and 1.6, the goal of this study was to analyse the impact of injection pressure, vacuum assistance during injection and the impact of hydrostatic pressure during the curing stage of the RTM process, for the quality of the surface finish. For the purpose of this learning process, the Sensor Nose Cone was used as an example to test and implement the findings.

Figure 12 was used as an initial reference for the development of the experimental approach. Based on it, a second schematic was created as is illustrated in Figure 14, which depicts an unplanned iterative approach. From this diagram, it was possible to estimate that this approach would be unfeasible, since it would lead to a very complex experimental process to study the effect of all the parameters and its combinations. Moreover, it was taken into account the complexity of producing a single Sensor Nose Cone, due to the process of draping the fibres in the lay-up, as well as the costs that would have been associated to each experiment

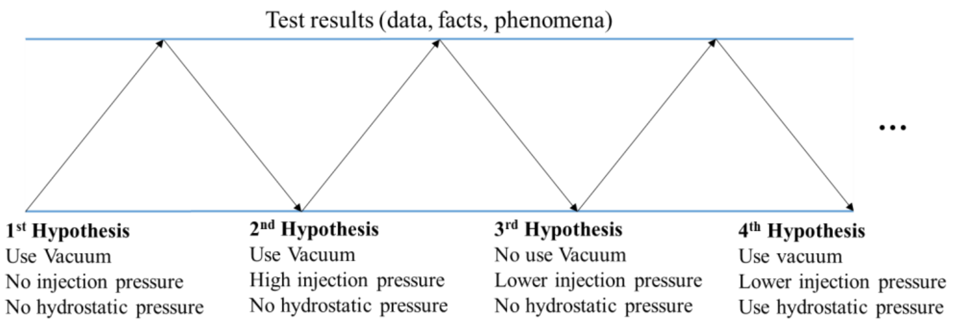

Figure 14 - Iterative learning method using the Sensor Nose Cone

Thus, to improve the learning process it was necessary to use techniques from design of experiments, in order to make the experiments as efficient and effective as possible. The changes to the approach can be seen in Figure 15, and the process was optimized to only be executed two iterations of hypothesis using a Sensor Nose Cone, together with an intermediate learning process.

The initial hypothesis, in which was used a Sensor Nose Cone, was planned to reflect the conclusions made from the literature reviewed.

Following, it was made an intermediate learning process that functioned as a data collection stage about the process parameters of this study. In this intermediate stage were used flat composite panels to represent the true state of nature, in order to avoid using Sensor Nose Cones to the data collection, due to the complexity of their production, which was already referred.

The last stage matches with the process of the second hypothesis, which was planned based on the conclusions made from the intermediate learning process. As in the first hypothesis, it was used once again a Sensor Nose Cone for the experiments.

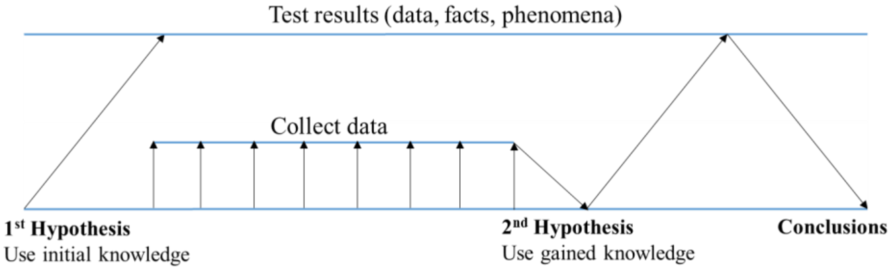

Figure 15 - Diagram of the selected approach for this study

3.3. METHOD

The development of an approach can be seen as a process of structuring in which a frame is built to hold the experiments. The task of defining the methods is a process of organizing the experiments inside the frame that was built. Having a well-organized methodology, makes it easier to find the solution inside the frame.

As described in Section 3.2 and illustrated in Figure 15, the approach devised can be separated in three stages. In the first stage was defined an initial hypothesis, which was used for the first iteration using the Sensor Nose Cone. The initial hypothesis was built by resorting to the knowledge collected in the literature. After defining the hypothesis, the execution of the experiment took place. Then, the results from the first iteration were compiled and saved, but contrary to the initially planned, these were not analysed nor used to generate a second hypothesis for the next stage.

Instead, it was executed a designed experiment as a second stage, in which was replicated the true state of nature, characterized by being simpler to implement and by consuming less resources than the one that used the Sensor Nose Cone. The purpose of the second stage experiments was to measure the effects of the three variables on void content at the surface of the laminate. To accomplish this task, it was used a two level factorial design, which is further described with more detail in Sub-Section 3.3.1 and in Appendix C.

Finally, the third stage, which corresponds to the second iteration of the Sensor Nose Cone, makes a hypothesis that was built from the conclusions derived from the designed experiments. Then, the results from the first iteration using the Sensor Nose Cone were compared with the second iteration and a conclusion from the results was discussed.

3.3.1. FACTORIAL DESIGN AT TWO LEVELS

According to Hunter *et al.* [8], factorial design is composed by a set of variables, denominated as factors. For each variable it is selected a fixed number of versions, also called levels, and the experimental tests are done using all the possible combinations of the variables. For example, in a situation in which is pretended to experiment three variables, v_1, v_2 and v_3, if v_1 has four variations, v_2 has five variations and v_3 has two variations, thus forty experimental runs are necessary to make the complete set of combinations. Whereas, with factorial design at two levels, each variable only has two variations, making a total number of runs to complete all the combinations of eight, thus reducing the amount of time and cost for these experiments.

Since factorial design at two levels limits each variable to two levels only, this characteristic restricts its capacity to investigate a wider panel in the factor space. Thus, this method is used to identify trends. For that reason, factorial design at two levels is used to determine promising directions, either as a filter for further experiments or as a guide to create concepts for implementation.

Based on the arguments explained above, factorial design at two levels was used to study the variables injection pressure, vacuum assistance and hydrostatic pressure in the intermediate learning process.

3.3.2. GRADING SYSTEM FOR THE CLASSIFICATION OF THE RESULTS

The method selected to evaluate the results from the experiments, of the factorial design at two levels, was based on a qualitative grading system, which use a visual inspection, assisted with a microscope. The grading system classifies the results of each experiment, in a scale from one to five and is fully described below:

- Grade 1: is given to a complete failed laminate, meaning that there is a combination of a dry spot and a large quantity of voids.
- Grade 2: is used to describe a laminate without one of the defects, but its quality is still unacceptable.
- Grade 3: classifies a panel with a reasonable quality, which still a considerable amount of voids.
- Grade 4: describes a panel with almost no voids.
- Grade 5: is given to a panel with no visible voids, and a very low quantity of porosities.

The other option would have been to use a quantitative approach, counting the number of voids and porosities in a defined area. This approach was discarded, due to the difficulties of defining an appropriate region to make the measurements that would represent an entire specimen, as well as the difficulties associated to the counting of the exact number of porosities and voids in the constrained region.

3.4. CONCLUSIONS

The knowledge obtained by learning about iteration using designed experiments (data collection stage), allowed to avoid using an inappropriate standard iterative approach. Instead, it was tailored a strategy capable of meeting the requirements for this specific study. This resulted in the creation of an efficient approach that contained the necessary methods to study the variables, and in which the true state of nature of the RTM process for the Sensor Nose Cone was guaranteed.

The division of the approach in three sections allowed to apply an initial hypothesis based on the principles learned from the literature, and afterwards compare them with a second hypothesis created based on the data collected from a designed learning process. The approach illustrated in Figure 14 was discarded because of its inefficiency as well as uncertainties regarding the usefulness of the experimental runs to yield the necessary data to generate a second hypothesis for the RTM process.

Factorial design at two levels was the selected method to organize the intermediate learning process. This method was chosen due to its capacity to indicate the impact of each variable, while using a lower number of experimental runs.

Due to the difficulties associated with using quantitative measurements to evaluate the results from the experiments, it was decided to use instead a qualitative system, which grades the results using a scale from 1 to 5. Despite the subjectivity associated with a qualitative grading system, it was considered that this method would provide enough detail to be able to differentiate the results.

Lastly, it should be noticed the importance of delineating the chosen strategy in order to perform the necessary experiments efficiently and to collect the data as efficiently as possible.

CHAPTER 4. IMPLEMENTATION

This chapter is focused in presenting how the approach and methods were implemented in order to initiate the learning process. The chapter starts with a description of the process of defining the initial hypothesis and its implementation in order to produce a Sensor Nose Cone. Following, it is made a description about the designed experiments for the intermediate learning process, as well as about the implementation of factorial design at two levels. The chapter finishes with a short conclusion about the challenges of implementing each task.

4.1. INITIAL HYPOTHESIS

The present section is focused on explaining and presenting the decisions made for the initial hypothesis. This section starts by defining the three process parameters, based on the reviewed literature. Afterwards are explained the procedures for the RTM process. Finally, are presented the assumptions made for the expected results.

4.1.1. VACUUM ASSISTANCE

In most RTM applications, the use of vacuum is considered essential. Nevertheless, for the initial hypothesis of this project it was decided not to use vacuum assistance. The reason for not using vacuum can be justified by the high probability of having a leak in the mould sealant. Thus, such would result in an air stream from the outside of the mould to the outlet ports, consequently leading to the entrapment of air bubbles.

The source of the leak in the mould cavity was believed to be originated at the O-ring joints. In this experiment, there were two factors that contributed for the appearance of the leak, the first being related with the design of the seal grove, and the second being related to the production process of the O-ring. In Figure 16, it is schematized the intersection of the T-joint with the mould surfaces. In the scheme, the red curved line, inside the circled region, points the area that was not being effectively compressed vertically, thus facilitating the passage of air.

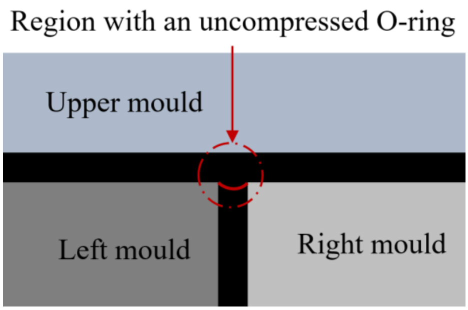

Figure 16 – Representation of the O-ring, the T-joint and the grove faces

The O-ring with the T-join used for the experiment is illustrated in Figure 5. Figure 17 illustrates the bonded joint, in which it is also possible to observe the flaws that could cause leak in the sealing. By analysing this image, it is possible to conclude that, as described in Section 1.2 the process used to fabricate the O-ring with the T-joint was not suitable for the case, but due to cost limitations and as there were no other options, the study had to continue with this joint.

Figure 17 – Glued T-joint of the O-ring

Since the first hypothesis does not use vacuum assistance during injection, it can reduce the degree of penetration of the resin in the fibres. Therefore, such ought to be compensated with the injection pressure.

4.1.2. INJECTION PRESSURE

The process of defining the injection pressure can be considered complex, since it has to be adjusted in order to guarantee that the resin penetrates through the fibres and that the injection process is completed before the resin reaches the gel point. Hence, in order to define the optimal value for the injection pressure it is necessary to know its relation with flow speed.

To study the relation between injection time and injection pressure, were made simulations using Finite Element Analysis (FEA) based on Darcy’s Law, which is used to calculate the flow speed based on the permeability of the material and the pressure gradient between the inlet and outlet ports, shown in Eq. 1 from Appendix A. The flow speed is then used to find the flow rate of the resin, and finally the injection time is calculated by dividing the mould cavity volume by the flow rate. To execute the simulations using Darcy’s Law, it was also necessary to perform an additional experiment focused on determining an approximate value of the laminate permeability. It is important to note that the simulations made did not predict how the resin would flow inside the mould cavity, as well it did not consider the necessary bleeding time to extract the remaining entrapped bubbles. A full description of the permeability experiments and of the injection time simulations are provided in Appendix A and Appendix B, correspondently.

Comparing the gel time of the resin matrix, Araldite® LY 1564 / Aradur® 3486, and the results obtained from the injection simulation, it was possible to conclude that, in this case, the gel time would not constrain the injection pressure. Such can be justified by the fact that even when a low pressure gradient is applied, i.e. 0.5 bar, the injection time is shorter that the gel time of the resin system. Thus, the only parameter constraining the injection pressure would be the level of penetration.

Then, for the initial hypothesis, it was decided to start the injection process at 0.25 bar. After five minutes, the injection pressure was increased to 0.5 bar and maintained for ten minutes. From then on, the injection pressure was increased every five minutes with 0.5 bar increments until reaching a final value of 3 bar.

4.1.3. HYDROSTATIC PRESSURE

As explained in Section 2.4, the hydrostatic pressure can be used in order to keep the volatiles in solution. Additionally to that, in this application, the hydrostatic pressure was also used to increase the degree of penetration of the resin.

Based on the saturated water vapour pressure, and considering that the curing temperature was 100 ºC, the applied hydrostatic pressure had to be above the atmospheric pressure, 1.0133 bar. Since the mould cavity did not have pressure transducers, it was necessary to consider that, due to pressure losses, the hydrostatic pressure inside the mould cavity would be equal or lower than the pressure applied in the resin pot. As there are no references stating that using a high hydrostatic pressure can cause void formation or any other type of defect, it was decided to apply 3 bar at the resin pot, during the curing process.

4.1.4. PROCEDURES

This section presents the list of procedures used to carry out the experiment. This was made in order to have a list of instructions, which assisted the experiment, so that each task could be done and checked along its execution.

1. <u>Tool warm-up:</u> started heating the mould to the injection temperature of 40ºC and maintained for thirty minutes to obtain a uniform heat distribution.
2. <u>Pressure regulation:</u> before closing the resin pot, the pressure valve had to be adjusted to 0.25 bar. This was necessary in order to avoid shooting the resin faster than planned.
3. <u>Open injection valve:</u> released the pinch valve at the exit of the resin pot, allowing the resin to start flowing.
4. <u>Injection process:</u> as defined in Sub-section 4.1.2, the injection process started at 0.25 bar and, was increased after five minutes to 0.5 bar, being maintained for ten minutes. After that, every five minutes, the pressure was increased by 0.5 bar increments until a pressure of 3 bar was reached.
5. <u>Control outlet ports:</u> forced a uniform exiting flow through all the outlet ports. In the case the matrix only came out from a single outlet port, this one had to be closed in order to achieve an even distribution through all the ports.

6. Close all outlet port: once a uniform resin stream was achieved in all outlet ports, these were closed. Note that the exiting flow did not need to be clear of bubbles. Closing all the outlet ports stopped the resin flow and increased the pressure inside the mould cavity.
7. Bleeding process: while maintaining the pressure at 3 bar, all the outlet ports were opened and closed one by one. Once a port was open, it should be closed only when the exiting stream contained a residual quantity of bubbles. The purpose of that was to allow the exit of entrapped air bubbles in the regions of each outlet port.
8. Close all outlet ports: after the bleeding process, once a clear stream came out from all outlet ports, all had be closed.
9. Adjust to curing pressure: adjusted the pressure at the resin pot to create a hydrostatic pressure. The pressure value was 3 bar.
10. Raise temperature: after adjusting the pressure at the resin pot, the mould temperature could be increased to 100 ºC, corresponding to the curing temperature.

4.1.5. ASSUMPTIONS

For the initial hypothesis it was decided not to use vacuum assistance, because of the risk of creating an air flow due to a possible leak in the sealant. Since vacuum was not used during the injection process, it was assumed that regardless the injection pressure, air bubbles would always be entrapped in the laminate. Yet, it is believed that due to the flow speed, the quantity of entrapped voids would be larger with an increased injection pressure. Therefore, it was necessary to develop a technique that used the injection pressure in order to reduce the quantity of voids.

In the devised method, the resin viscosity was reduced by increasing the injection temperature of the mould to 40 ºC, together with the use of a low injection pressure during the first fifteen minutes of the injection process, in order to avoid dry stops and ensuring a proper distribution of the resin inside the mould cavity.

The pressure was then increased in order to fill the mould cavity as fast as possible, but one of the risks of increasing the flow speed was to create large dry spots. Thus, as explained in Sub-section 4.1.4, it was necessary to control the outlet ports before closing them.

Once all outlet ports were closed, the resin flow was stopped and the pressure inside of the mould cavity increased to approximately 3 bar. This increment caused a reduction of the air bubbles size, thus increasing their density. By reducing their size, the movement of the bubbles was easier, but the increased density resulted in lower buoyancy. This effect combined with the vertical orientation of the mould facilitated the upstream flow of the air bubbles in the direction of the outlet ports.

The key technique used to replace the vacuum assistance was the bleeding process, which worked as a controlled gating of the outlet ports. This technique allowed the escape of the accumulated air bubbles in the region of the opened outlet.

Finally, besides preventing the evaporation of volatiles during curing, it was also expected that the degree of penetration of the resin would improve from the applied hydrostatic pressure.

4.2. DESIGNED EXPERIMENTS FOR INTERMEDIATE LEARNING PROCESS

The information provided in this Section is a resume of Appendix C. The designed experiments were developed with the purpose of replicating the same process conditions of the Sensor Nose Cone, while reducing the lay-up complexity. On that basis, instead of using the Sensor Nose Cone mould, it was used a mould for flat panels shown in Figure 19, which was sealed using a glued O-ring, as shown in Figure 18. Regarding the fabrication of the panels, these were made using the same material as for the Sensor Nose Cone.

Figure 18 – O-ring ends being glued

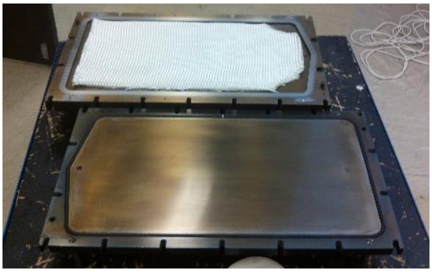

Figure 19 – Moulds and lay-up for flat panels

As stated in Sub-Section 3.3.1, the method selected to organize the experiments was a factorial design at two levels. This method was selected due to its simplicity and capacity to indicate behaviour trends. The application of this method to study injection pressure, vacuum assistance and hydrostatic pressure limits each variable to only two variations making a total of eight possible combinations. In Table 2 are compiled all the possible combinations for a two level factorial design, together with the assigned values for each variable.

Table 2 – Experimental combinations and the values assigned to each variable

Test Number	Injection pressure	Vacuum assistance	Hydrostatic pressure
1	-	-	-
2	+	-	-
3	-	+	-
4	+	+	-
5	-	-	+
6	+	-	+
7	-	+	+
8	+	+	+

	Injection Pressure [bar]		Vacuum Pressure		Hydrostatic Pressure [bar]	
Symbol	-	+	-	+	-	+
Values	0.5	5	OFF	ON	0	5

As explained in Sub-section 3.3.2, to evaluate the results obtained from each panel, it was chosen a qualitative grading system based on visual inspection assisted with a microscope. The grading scale ranges from one to five. A grade one classifies a failed laminate, which has a combination of a dry spot and a large quantity of voids. On the opposite side of the scale, a grade five is given to a laminate without any visible voids, and a very low amount of porosities. The results obtained are then displayed via a geometric representation, as the example shown in Figure 20, capable of displaying the relations between changes in the process parameters.

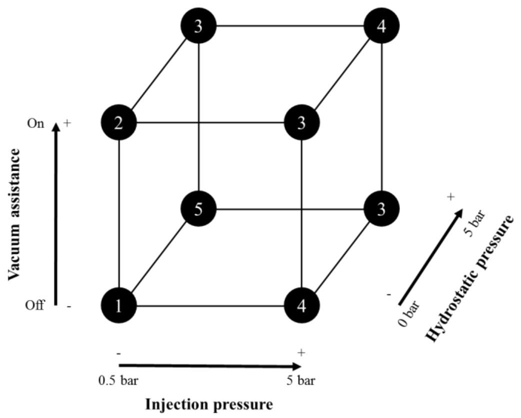

Figure 20 – Example of a geometric representation for a factorial design at two levels

4.3. SECOND HYPOTHESIS

As explained in Section 3.2, the second hypothesis was built based on the conclusions derived from the intermediate learning process. Therefore it was decided not to include in this chapter the implementation of the second hypothesis for the Sensor Nose Cone, because that was made after obtaining the results from the intermediate learning process.

Thus, the description of the process for the second hypothesis is made in Section 5.3, after the presentation of the results of the intermediate stage.

4.4. CONCLUSIONS

By comparing the process of creating and implementing the initial hypothesis with the preparations for the design experiments, it becomes evident that using the factorial design at two levels was the correct choice for the intermediate learning process. Because of its complexity, using the Sensor Nose Cone to study the influence of the three process parameters, would create difficulties to identify the causes responsible to the changes in the results. While with factorial design at two levels, the experimental preparations are simpler, and it provided a better organization of the experiments. Thus, making it easier to interpret the results by presenting them in a more meaningful way, in which is possible to see the changes in the responses associated with a change in the variables.

In this chapter is not presented the implementation of the second hypothesis because it was made based on the experiment of the intermediate stage with the best results. For that reason its implementation is discussed in the following chapter.

CHAPTER 5. RESULTS

In this chapter the results from each experiment are presented in separate sections, and then the results are discussed in the conclusions. Due to the nature of the approach defined in Section 3.2, this chapter is organized in a chronological manner, since each step was performed sequentially.

5.1. INITIAL HYPOTHESIS

In Figure 21 is a side view photography taken of the resultant part. From it is possible to distinguish the four regions of the laminate, it must be noted that the second regions has a darker appearance because of the background. Considering that this was the first experiment using the Sensor Nose Cone, the results from the initial hypothesis showed positive results, achieving a part quality that could be classified with a three by using the same scale system as in Sub-section 3.3.2.

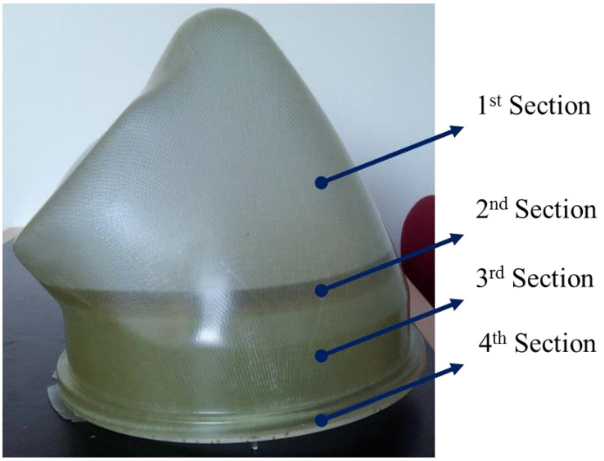

Figure 21 - Side view of the result from the initial hypothesis, with a description of the lay-up sections

The obtained part was classified with a three, due to the quantity and size of voids and to the low degree of penetration in some fibre bundles. The photography shown in Figure 22 captures some of the voids present in the second section of the Sensor Nose Cone laminate. When examining the part, it was observed that in the region correspondent to the first section there were almost no voids and the ones present were relatively small. It was also possible to notice that the void quantity and their size increased in the second section and above. Regarding the degree of penetration of the resin, as shown in Figure 23, the fibre bundles with a whiter coloration indicated that the inside of the fibre bundles might be dry, thus meaning a low degree of penetration of the resin.

A positive outcome of this experiment was the part surface finish, which was free of irregularities caused by voids, with the exception of the regions close to the outlet ports, as shown in Figure 24. An unexpected result was injection time, which without counting with the bleeding process, took forty three minutes.

Figure 22 – Voids present in the second section

Figure 23 – Fibre bundles with a low degree of penetration

Figure 24 – Voids in the surface close to the outlet ports

5.2. DESIGNED EXPERIMENTS FOR INTERMEDIATE LEARNING PROCESS

As in Section 4.2, here is presented a summary of Appendix C with the results obtained in the intermediate learning process. Table 3 displays the grades for each test panel, together with comments about the quality of each panel. The results are then compiled and presented in a geometrical representation in Figure 25. Finally, pictures of each panel can be found in Appendix C.

Table 3 - Experiment combinations with the corresponding grades

Test Number	Combination	Grade	Comment
1	- / - / -	2	• High quantity of voids • Large area with low penetration
2	+ / - / -	1	• Large dry area • High quantity of voids
3	- / + / -	4	• No visible voids • Low quantity of porosities • Low degree of penetration
4	+ / + / -	1	• Large dry spots • High quantity of voids
5	- / - / +	4	• Low quantity of voids • High degree of penetration • High quantity of porosities
6	+ / - / +	2	• Large dry spots • Fibre distortion • High degree of penetration • Low quantity of voids and porosities
7	- / + / +	5	• No visible voids • Low quantity of porosities • Excellent degree of penetration
8	+ / + / +	4	• Dry spot • High degree of penetration • Low quantity of voids and porosities

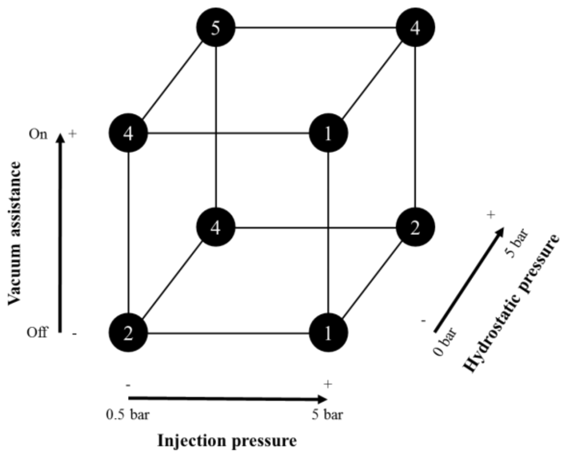

Figure 25 – Geometrical representation of the results

5.3. IMPLEMENTATION AND RESULTS OF THE SECOND HYPOTHESIS

5.3.1. IMPLEMENTATION OF THE SECOND HYPOTHESIS

The purpose of this sub-section is to present and explain the second hypothesis for the RTM process of the Sensor Nose Cone. As explained in Section 3.3, the second hypothesis was built based upon the conclusions collected from the results of the intermediate learning process. Similarly to Section 4.1, this sub-section begins with a description about the values of each parameter for the second hypothesis, then a summary of the procedures for the RTM process is presented, followed by an explanation of the expected results.

5.3.1.1 Vacuum Assistance

It is possible to observe, from the results of the intermediate learning process, by comparing the top and bottom plane of the geometrical representation in Figure 28, that even with a leak in the sealing of the mould, using vacuum assistance during injection, improves the quality of the laminate. Based on these results, it was decided to use vacuum during the injection stage of the process.

5.3.1.2 Injection Pressure

In the intermediate learning process, it was found that using a high injection pressure can lead to the creation of large dry spots in the laminate and, opposite to that, using a low injection pressure leads to a lower void content as well as prevents the appearance of dry spots. When defining the injection time, it was necessary to consider that the injection process of the initial hypothesis took longer than expected. Therefore, using a low injection pressure could result in an incomplete injection of the mould cavity. Despite that risk, since this approach used vacuum, which increases the pressure gradient and consequently improves the flow of the resin, it was decided to use a constant injection pressure of 0.5 bar for the second hypothesis.

5.3.1.3 Hydrostatic Pressure

Based on the results obtained from the test panels, in Section 0, it became obvious that increasing the hydrostatic pressure seemed to only improve the laminate quality by increasing the degree of penetration of the resin and reducing void content. Therefore, the curing temperature was maintained, but the hydrostatic pressure was increased from 3 to 5 bar in the second hypothesis experiment.

5.3.1.4 Procedures

As in Sub-Section 4.1.4, here are presented a resumed list of the procedures taken for the RTM process using the second hypothesis:

1. <u>Tool warm-up:</u> started heating the mould to the injection temperature of 40ºC, and maintained it for thirty minutes to obtain a uniform heat distribution.
2. <u>Pressure regulation:</u> before closing the resin pot, the pressure valve had to be adjusted to 0.5 bar.
3. <u>Apply vacuum:</u> Opened the vacuum valve in order to create vacuum inside the mould cavity. Maintained it open.
4. <u>Open injection valve:</u> After opening the vacuum valve for 5 minutes, the pinch valve at the exit of the resin pot was released, allowing the resin to start flowing.
5. <u>Injection process:</u> Maintained injection pressure at 0.5 bar and continued using vacuum assistance.
6. <u>Control outlet ports:</u> forced a uniform exiting flow through all the outlet ports. In the case the matrix only came out from a single

outlet port, this one had to be closed in order to achieve an even distribution through all the ports.

7. Close all outlet port: once a uniform resin stream was achieved in all outlet ports, these were closed. Note that the exiting flow did not need to be clear of bubbles. Closing all the outlet ports stopped the resin flow and increased the pressure inside the mould cavity.
8. Close vacuum: stopped the vacuum assistance and released the vacuum to create an atmospheric pressure in the outlet ports.
9. Apply hydrostatic pressure: before the bleeding process, the injection pressure was increased to 5 bar and maintained during two minutes.
10. Lower pressure: After applying a pressure of 5 bar during two minutes, the pressure was lowered to 0.5 bar.
11. Bleeding process: while maintaining the pressure at 0.5 bar, all the outlet ports were opened and closed one by one. Once a port was open, it should be closed only when the exiting stream contained a residual quantity of bubbles. The purpose of that was to allow the exit of entrapped air bubbles in the regions of each outlet port.
12. Close all outlet ports: after the bleeding process, once a clear stream came out from all outlet ports, all had to be closed.
13. Adjust to curing pressure: adjusted the pressure at the resin pot to create a hydrostatic pressure. The pressure value was 5 bar.
14. Raise temperature: after adjusting the pressure at the resin pot, the mould temperature could be increased to 100 ºC, corresponding to the curing temperature.

5.3.1.5 Assumptions

For the second hypothesis, it was decided to use vacuum assistance during the injection process, until resin flowed out of the outlet ports. After the injection was completed, the vacuum assistance was shut down and the pressure of the outlet ports raised to the atmospheric pressure. This decision replicates the procedures used for the designed experiments of the intermediate learning process, in which was demonstrated that having a leak in the sealing of the mould and using vacuum assistance would not lead to the formation of voids.

The choice of the injection pressure was made based on Figure 29, from which is possible to see that using a lower injection pressure would lead to a lower void content of the laminate. However, using such a low injection pressure would increase the risk of having an incomplete injection process. In spite of that, it was considered that, since it was used vacuum assistance, the pressure gradient would be enough to make the resin flow through the lay-up.

Similarly to what was done in the initial hypothesis, for the second hypothesis it was also decided to bleed the mould cavity. This procedure may seem unnecessary because the process used vacuum assistance, and theoretically, there would not be any entrapped air to remove by bleeding the mould. But since the seal had leaks, there was a certain amount of air bubbles caused by the flow stream of air from the outside to the inside of the mould, in the direction of the vent ports. In the procedure list in Step 9, before bleeding the mould it was applied a hydrostatic pressure of five bar. This was done with the purpose of increasing the degree of penetration of the resin matrix, as well as push the voids in the direction of the outlet ports.

Finally, the hydrostatic pressure was applied based on the same reasons as the initial hypothesis, but in this case it was increased to five bar. This adjustment was made, because the results from the experiments of the intermediate learning process did not show signs of negative effects from applying a higher pressure than the necessary to overcome the saturated vapour pressure.

5.3.2. RESULTS OF THE SECOND HYPOTHESIS

The results from the second hypothesis are visible in Figure 26. From it, is possible to see that with this approach the quality of the Sensor Nose Cone is much lower than the one with the initial hypothesis. Although unexpected, the Sensor Nose Cone laminate was not fully wet, thus resulting in large dry spots. Besides that, were also identified large voids, mostly in the resin rich area of the second section and near the inlet port. Additionally, despite using a higher hydrostatic pressure, the degree of penetration of the resin matrix is clearly lower than the one obtained with the initial hypothesis. Such is evident by the whiter colour of the fibre bundles.

Another unexpected result was the time required to complete the injection procedure, which was seventeen minutes. Comparing this result with the value obtained in the simulation of the injection time for scenario two, in Appendix B, it shows that the injection time calculated from the simulation almost meets the experiment, which was not the case in with the first hypothesis.

a) Front view
b) Back view

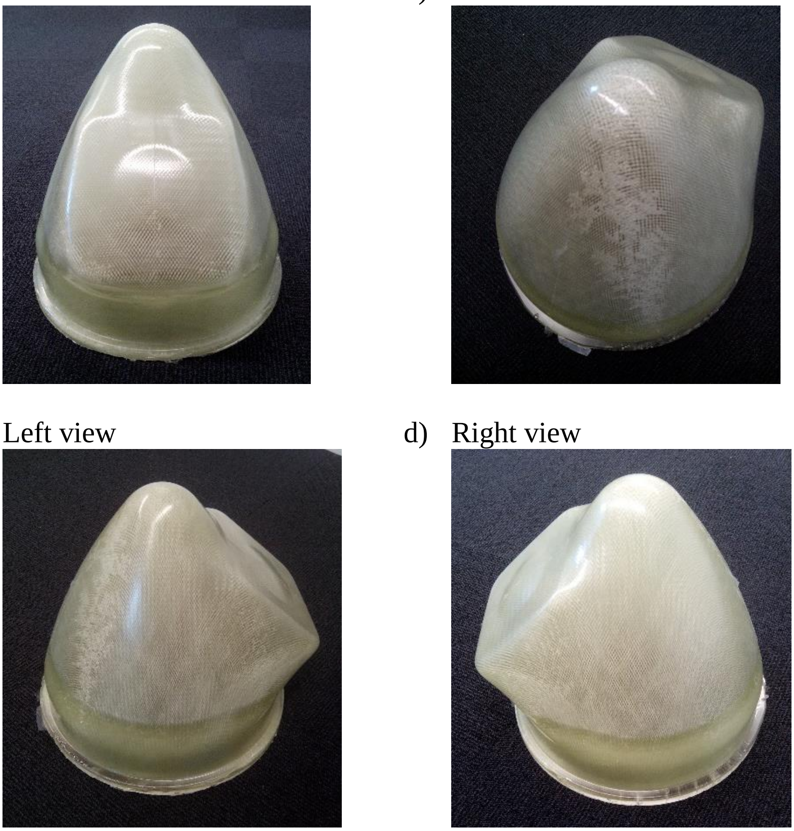

Figure 26 – Images of the Sensor Nose Cone produced using the second hypothesis

5.4. CONCLUSIONS

In this section are discussed the conclusions derived from the results obtained with the experiments made. The section follows the same order as the previous sections, starting with the results of the initial hypothesis, being followed by the intermediate learning process and by the second hypothesis. Finally, the chapter resumes with an overall conclusion about the results obtained in this study.

5.4.1. INITIAL HYPOTHESIS

The hypothesis used for the first experiment with the Sensor Nose Cone proved to meet the assumptions made, and demonstrated to be an effective approach by achieving a good quality part. By comparing the results obtained with the initial hypothesis and the test panels from the intermediate learning process, it becomes noticeable that the panel from test five, that used a low injection, no vacuum and five bar of hydrostatic pressure, had similar type of defects. Such can be explained by the resemblances of the injection approach.

The defects identified in the laminate correspond to the quantity and size of voids and to the low degree of penetration in some fibre bundles. Regarding void content, it was noticed that the first section of the laminate did not contain visible voids to the naked eye. Therefore, it is considered that the voids from the first section travelled upwards, in the direction of the vent ports, and when the bleeding process stopped these got trapped in the above sections of the laminate. Thus, void quantity could have been reduced by continuing the bleeding process. Additionally, it must be noted that the quantity of voids in the surface of the laminate was residual, such is considered to be a result of the vertical orientation of the mould, and the upstream flow of the resin, as demonstrated in Figure 41 from Appendix B. In relation to the degree of penetration of the resin, it is believed that it could have been improved by increasing the hydrostatic pressure before the curing process.

Finally, it was expected that the injection process would have been completed in thirty minutes, after increasing the injection pressure to two bar. However, this did not happen and the discrepancy between the expected injection time and the actual result indicates the presence of a parameter causing an increase in the flow resistance, thus slowing the injection process. The differences in the results obtained is believed to have been caused by the difficulties of draping the fibres always in the same way. Therefore, the fibre angles of the laminate for the initial hypothesis must have been different from the ones used to study the permeability of the material (Appendix A).

5.4.2. DESIGNED EXPERIMENTS FOR INTERMEDIATE LEARNING PROCESS

Using a factorial design at two levels revealed to be an effective and efficient strategy to study the impact of RTM process parameter in void content in the surface of the laminate. By looking at Table 3, it is possible to observe that no panel got a grade three, meaning that the data collected represents only the extreme responses towards the change of variables. Thus, proving that factorial design at two levels is an appropriate method to indicate behavioural trends caused by changes in the variables. Also, the geometrical representation in Figure 25 proved to be a very useful method of displaying the results, by facilitating the analysis of different combinations of variables and their impact in the laminate quality.

As explained in Appendix C, the geometrical representation of the results allowed to establish several relationships between the variables. In Figure 27 are used red arrows to point out how the quality of the laminate can be improved by changing one or more variables. Additionally, another three relationships are made. In Figure 28, it is made a comparison between the bottom and top planes of the cube, showing that the quality of the laminate increases by using vacuum assistance. A similar technique is used in Figure 29 to compare the left and right side of the cube, demonstrating that reducing the injection pressure leads to a reduction in void content and prevents the creation of dry spots. Regarding the hydrostatic pressure, the experiments showed that it is more effective when using a low pressure gradient, because with a higher flow speed the risk of creating a dry spot increases, and from the results it appears that the hydrostatic pressure by itself is not enough to compensate the dry areas.

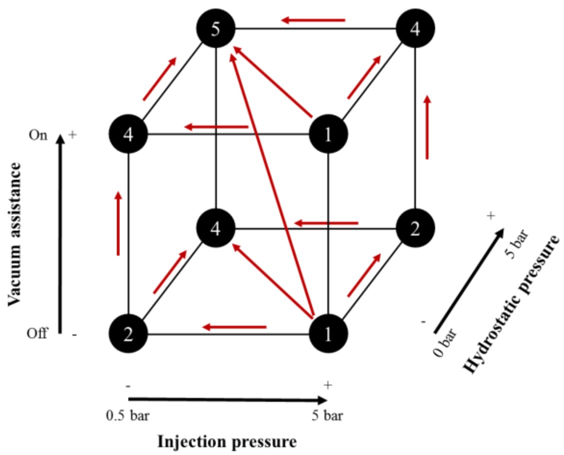

Figure 27 – Geometrical representation of the results, with relationship arrows

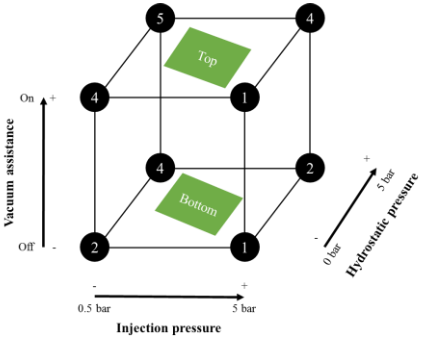

Figure 28 – Geometrical representation with the highlighted top and bottom planes

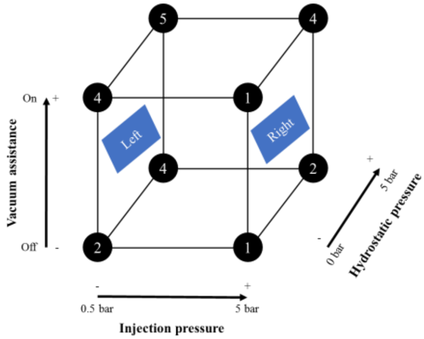

Figure 29 – Geometrical representation with the highlighted left and right planes

An interesting relation is made between test 5 (-/-/+) and the initial hypothesis, since both used similar values for the process parameters, and achieved similar results. From the designed experiments, it was possible to answer the concerns of using vacuum for the initial hypothesis. In the experiments, it was possible to realize that there is no relevant effect on void content for the tests with vacuum assistance, then using a seal with a purposely made leak.

It must be noted that in test 6 (+/-/+) and 8 (+/+/+), the dry spots can be explained as a result of fibre wash, which pushed the fibres towards the outlet port, thus clogging it.

The most positive outcome of this method was the possibility to easily define the parameters for the second hypothesis. By consulting the Figure 27, the optimal solution was to use a combination of vacuum assistance, low injection pressure and a high hydrostatic pressure. Nevertheless, it must be mentioned that, since each experiment was performed only once, it was not possible to analyse an eventual influence of external parameters in the results obtained in the present study.

5.4.3. SECOND HYPOTHESIS

The results obtained with the second hypothesis were not exactly the same as the ones expected. From this experiment, it was assumed that the quality of the laminate would be free of voids and with a high degree of penetration, as the panel from test number 7 (-/+/+) of the intermediate learning process. After evaluating the results, it was necessary to attempt to understand the causes of the discrepancies.

The first thing was to look back at the experience made in the intermediate learning process. The purpose of this stage was to implement a simpler experiment, that represented the true state of nature of the RTM process for the Sensor Nose Cone. By analysing pictures of the preparations of both experiments, it was noticed that the relative position of the inlet and outlet ports were different. This is evident by comparing Figure 30 and Figure 31. In the designed experiments the inlet and outlet port are at the same level, being on the left side of the image the inlet, whilst the outlet port in the opposite side. In the case of the Sensor Nose Cone mould the inlet is at the bottom and the outlet ports are at the top. Such differences resulted into two distinct flow paths, thus meaning that each mould cavity is filled up differently. In order to avoid the discrepancies verified, the designed experiments should have been performed using the mould in a vertical position with the outlet port at the top.

Based on the results obtained from the second hypothesis, it is difficult to determine if the poor results achieved are justified by an inappropriate selection of the process parameters or if it was caused by an error during the execution of the process procedures.

Figure 30 – Preparations for the designed experiments

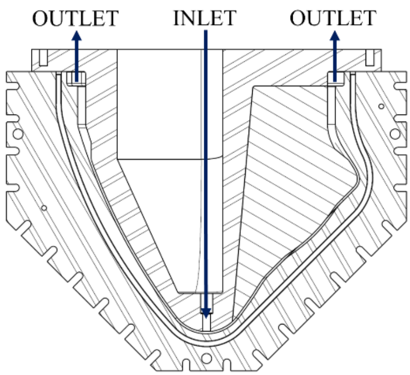

Figure 31 - Cross section view of the Sensor Nose Cone mould

Regarding the injection time, in this experiment the value determined by the simulations Scenario 2 from Table 7 from Appendix B, is much closer to the reality than the result obtained during the experiment of the initial hypothesis. Such difference in the injection time can only be explained by differences in the lay-up arrangement in the region of the inlet port. The lay-up of the first scenario must have created a higher resistance, thus slowing down the flow speed of the resin. The lay-up arrangement near the inlet port was considered the critical factor, because if the inlet port was obstructed it would not allow the resin to flow inside the mould cavity. Whereas, if the resin flow was blocked in another region of the lay-up, the resin would have probably flowed around it, thus creating a dry spot.

5.4.4. OVERALL CONCLUSION

From the results of the two hypothesis and from the intermediate learning process it was possible to make a new deduction about using vacuum assistance during the injection process. As it seems, using vacuum assistance affects the behaviour of the flow, depending on the position and orientation of the inlet and outlet ports.

Based on the results obtained, it is assumed that the flow behaviour of the second hypothesis can be described as capillarity rise of the resin assisted by vacuum pressure, being this phenomenon illustrated in Figure 32. In this type of behaviour the resin flows predominantly in-between and inside the fibre bundles, thus the surfaces of the laminate will not be properly wet. Another side effect of capillarity rise appears when the resin finds a path connecting the inlet to the outlet port. In these circumstances, the flow path will not alter, meaning that the regions in which the resin did not pass will be left dry. Whereas the initial hypothesis without using vacuum assistance, due to the difference in the materials densities, the resin has a tendency to maintain a levelled flow front.

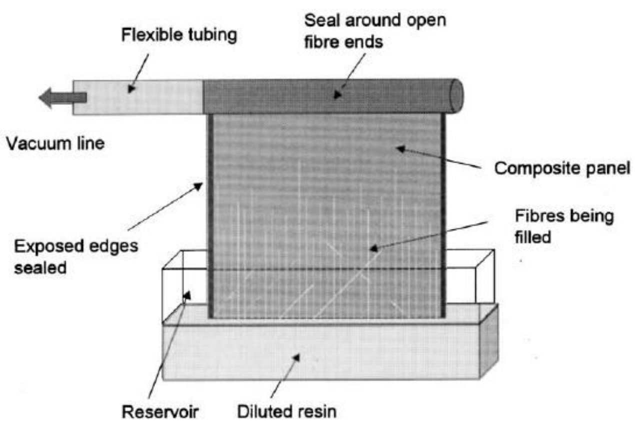

Figure 32 – Image taken from [9], illustrating the effect of vacuum assisted capillarity rise

In this study, it was not concluded why the hydrostatic pressure was not able to fill the dry spots when vacuum assistance was employed. This event contradicts one of the expected functions of the hydrostatic pressure, which is to increase the degree of penetration of the resin. Since there is not an explanation capable of justifying one of the assumptions about the hydrostatic pressure, it is considered necessary to re-evaluate the experimental procedures and then execute additional experiments with an appropriate number of samples.

Finally, it must be mentioned that after performing the experiments it was concluded that it would be more relevant for this study to use the injection flow rate of the resin matrix, than to use the injection pressure. Such conclusion was made after executing the simulations of the injection time, because, depending on certain situation, using a pressure of 0.5 bar does not mean that the flow speed is low. Thus leading to false assumptions and unexpected results. On the other hand, by using the injection flow speed parameter, it is assumed to be possible to define an ideal value.

CHAPTER 6. CONCLUDING REMARKS

In this chapter are depicted the final conclusions of the present study, as well as the suggestions for future investigation regarding the subject in question.

6.1. CONCLUSION

The primary research question is focused in understanding the impact of three RTM process parameters vacuum assistance, injection pressure and hydrostatic pressure, in the quality of the surface finish. During this study, the Sensor Nose Cone was used as a sample product, to which the conclusions derived from the literature and experiments are applied to.

The first effort with this project was to define a strategy to study the process parameters and apply them to the Sensor Nose Cone. The approach selected consisted of three main steps. Firstly, it was conceived and implemented, for the Sensor Nose Cone, an initial hypothesis which reflected the conclusions drawn from the studied literature. Afterwards, it was executed an intermediate learning process, which based on a designed experiment allowed to collect additional information about the behavioural trends caused by changes in each of the parameters in question. Finally, a second hypothesis for the Sensor Nose Cone was built from the conclusions of the intermediate learning process. The strategy defined proved to be very effective to speed up the learning process. Despite the effectiveness of the approach and method, the designed experiments proved to be inappropriate. Meaning that the designed experiments, did not replicate the conditions of the RTM process of Sensor Nose Cone accurately, which caused unexpected results for the second hypothesis. Additionally, it must be mentioned that in order to validate the veracity of the conclusions made it is necessary to make repetitions of each test run with a more significant sample.

Based on the results obtained from the first and second hypothesis, it was possible to understand that the process parameters selected for a RTM process should also take into consideration the position of the inlet and outlet ports, as well as the direction of the flow. Therefore, it is considered that to define an ideal RTM process it is necessary to consider more than just the three parameters studied here, as well as establishing relationships between the parameters. Nevertheless, this study allowed to experience a great insight into the manufacturing tasks related with the RTM process, as well as obtain experience and knowledge about defining RTM process parameters.

From the results collected it is possible to assume that for the manufacturing of the Sensor Nose Cone, the best approach is to use, during the injection stage, a low injection pressure and not use vacuum assistance. Once the injection process is completed, it should be applied a hydrostatic pressure at least higher than the saturated vapour pressure correspondent to the curing temperature.

Based on the expectations to reduce costs associated with the surface preparations before painting, it is considered that, despite the fact that in both implementations with the Sensor Nose the surface contained voids, the present work has contributed to improve the knowledge about the influence of some parameters in the surface quality of parts produced via RTM process. Moreover, it must be stated that further investigations have to be conducted to study this process, in order to continue to create added value to manufacturers, regarding improving alternative processes to be more efficient and to consume less resources.

6.2. PERSPECTIVES

Based on the problem statement and primary research question, correspondingly in Sections 1.3 and 1.6, the purpose of this study was to analyse the impact of the RTM process parameters; vacuum assistance, injection pressure and hydrostatic pressure in order to reduce void content at the surface of the laminate, thus improving the surface quality of the part. By defining such a narrow scope, it is understandable that this report covers only a fraction of the challenges in order to reduce void content and improve the quality of the laminate. After executing the experiments and analysing the results, it became obvious that, despite being crucial for the quality of the laminate, the selected parameters were not sufficient to allow a definition of an ideal approach to inject and cure parts manufactured via RTM, thus meaning that this study can be extended to other parameters.

Since the factorial designed at two levels proved to be an effective and efficient strategy to study the impact of RTM process parameter, it is considered that the same method can be applied in future studies to analyse the behavioural trends caused by other parameters.

As mentioned in the implementation of both hypothesis for the Sensor Nose Cone, the tool was preheated to 40 ºC in order to reduce the viscosity of the resin matrix, thus facilitating the passage of the flow front. When such was done it was not considered the influence of the viscosity for the escape of entrapped air, because it was assumed that having a lower viscosity could facilitate the escape of entrapped air bubbles and increase the degree of penetration. In order to confirm these assumptions is considered relevant to quantify the influence of the viscosity for the entrapment of air bubbles, dependent on the injection flow speed, in future projects.

During the execution of the experiments for the intermediate learning process with the flat panels, it was noted that for future studies, a possible solution to facilitate the analysis of the process is to use a transparent mould that allows to see inside the mould cavity. Despite its simplicity, it is considered that this approach can reduce the number of experiments in order to evaluate the effects of the process parameters. This approach could be implemented to analyse why in cases using vacuum assistance, the dry spots are not filled with resin even though it is applied a hydrostatic pressure, or also to observe the effect of having a leakage in the sealant.

The present study was only focused on reducing void content on the surface of the laminate and, to continue to improve the surface quality of parts produced via RTM, it is also necessary to study the thermal compatibility between the fibre reinforcement and the resin matrix. As explained by Campbell [3], the thermal mismatch between the fibres and the resin is a major cause of residual stresses, which can lead to distortions and irregularities on the surface of the part.

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APPENDICES

Appendix A. **Permeability Test**

Introduction

The purpose of the experimental test here presented was to determine an approximate value of the permeability, of the Sensor Nose Cone, in order to retrieve the necessary data to compute the simulations for the prediction of the injection time, described in detail in Appendix B. For simplicity reasons, this test just replicated the lay-up of the first and third regions of the part in study. As explained in Section 1.2, the Sensor Nose Cone may be divided in four different sections and in Figure 4 is possible to observe its scheme.

In what concerns permeability, as explained by Ochsner *et al.* [10] and Hoeksema *et al.* [11], it measures the resistance of a fluid to pass through a porous material. The measuring unit of permeability is square meters, and it represents the area of the open pore space perpendicular to the flow front.

There are several methods to study the macroscopic permeability of a porous material, but, the most applied one is based on Darcy’s Law. Despite that, the task if determining the permeability is still considered to be quite challenging, since it has not been yet been established a standard method for testing it and also due to the complex pore structure of a fibre material.

Method

Like in the work conducted by Amico *et al.* [12], the method selected to study the permeability was based in Darcy’s law.

First, it was made, a simplification was made in order to reduce the problem to a single dimension, also known as the one dimensional Darcy’s Law and expressed by Eq. 1. In this equation, v_x, k, μ and (dP/dx), are respectively the flow front velocity [m/s], the material permeability [m^2], dynamic viscosity [Pa.s] of the fluid and the pressure gradient [Pa] over the specimen.

$$v_x = -\frac{k}{\mu} * \frac{dP}{dx} \Leftrightarrow k = -\frac{v_x * \mu}{\left(\frac{dP}{dx}\right)} \qquad \text{Eq.1}$$

As illustrated in Figure 33, the designed experiment used a pressure gradient made by a vacuum pump, in order to push the resin matrix through a rectangular laminate. The necessary data to calculate the permeability was collected by visual means, while the resin flowed through the laminate, in which were registered the pressure gradient, the position of the flow front and the time that it took for the flow front to reach that position.

One of the challenges of this experiment was related with the irregularities of the flow front caused by the composite material. Such behaviour of the flow front is a result of the complex structure of the laminate porosities and not having a uniform flow front, can lead to high discrepancies in the permeability value, due to the fact that the method was based on the one dimensional Darcy's Law..

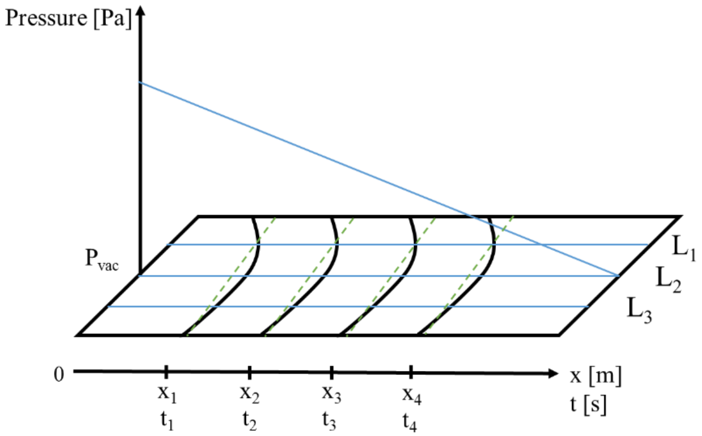

Figure 33 – Sketch of the experiment designed to determine the permeability

In order to reduce this effect, before entering the fibreglass laminate, the resin passed through a flow mesh, thus creating a more uniform flow front. The flow mesh is shown in Figure 34, in which is positioned on the left side of the lay-up with a green colour. As a second countermeasure, the measurements were taken in three different positions along the laminate, as illustrated in Figure 33 by the letters L_1, L_2 and L_3.

In Figure 34, are also shown the preparations for the experiment before bagging the specimens. As it can be seen, two specimen lay-ups were made for the first and third regions. This was done in order to have the possibility to evaluate the difference of the measured data, from two specimens with the same lay-up.

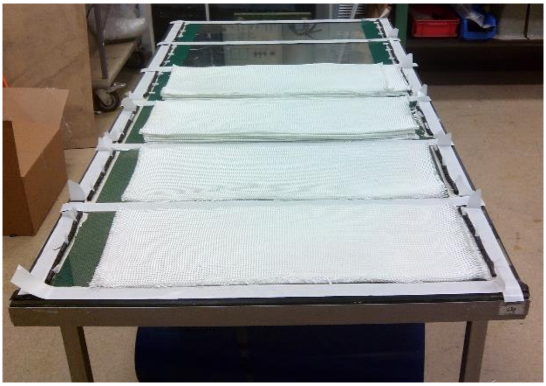

Figure 34 – Preparations before bagging the specimens

Results

The permeability values obtained from the experiment are exposed in Table 4 and Table 5. Despite the positive outcome of the experiment the results from one of the specimens of the first region was discarded. The reasons for not considering the results obtained from one of the specimens is justified by the irregularities of the flow front observed.

Table 4 – Permeability values obtained from the second specimen representing the first region

Line	Permeability [m^2]
L_1	1.2326×10^{-9}
L_2	1.3333×10^{-9}
L_3	1.2188×10^{-9}
Average	1.2616×10^{-9}

Table 5 - Permeability values obtained the third region

SPECIMEN 1

Line	Permeability [m^2]
L_1	5.36523×10^{-10}
L_2	5.73955×10^{-10}
L_3	4.93601×10^{-10}
Average	5.34693×10^{-10}

SPECIMEN 2

Line	Permeability [m^2]
L_1	6.84556×10^{-10}
L_2	8.06799×10^{-10}
L_3	7.53012×10^{-10}
Average	7.48122×10^{-10}

The irregularity becomes obvious when comparing the flow front of both specimens shown in Figure 35 and Figure 36. In the first picture, it is possible to see that an obstruction in the middle of the flow front only allowed the fluid to pass through the sides, while in Figure 36 the irregularities observed were as expected for a flow front, since they can be approximated to straight lines.

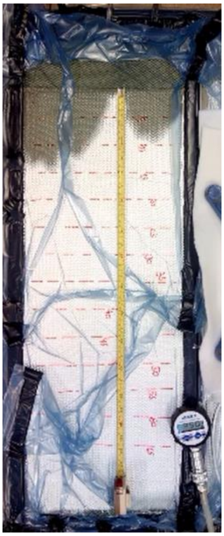

Figure 35 – Failed flow front

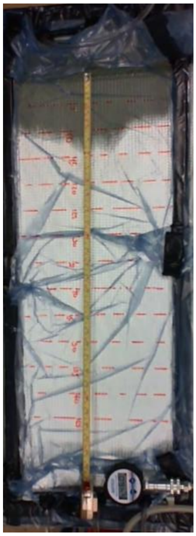

Figure 36 – Expected irregularities in a flow front

The cause of this problem is illustrated in Figure 37, and it was a result of the misplacement of the flow mesh, which was not contacting with the laminate fibres, thus allowing the bagging film to block the flow path.

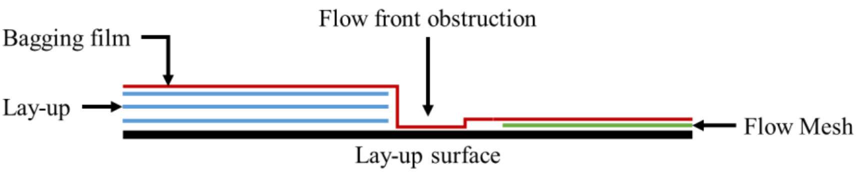

Figure 37 - Cause of the flow front obstruction

Discussion

Regarding the irregularities of the flow front, the method implemented using the flow mesh demonstrated to be effective. Yet, after completing the experiments, it was concluded that the specimens for a test based on the one-dimensional Darcy's law should not have been as wide as these were. This is due to the fact that narrower specimens would have provided results with less noise caused by non-longitudinal flow.

It should be also noted that Darcy's Law is only valid for homogenous materials with random porosities. Hence, despite not representing the reality, the values collected for the laminate permeability had to be considered as an isotropic property of the material.

In what concerns the permeability values that represented the first and third regions of the Sensor Nose Cone, they were defined as the average from the three lines of each experiment. However, the results from Specimen 2 of the third region were discarded due to conservative reasons, since if they were considered to the average between the two specimens, it would had led to a faster injection time that could have brought some problems during its execution.

Finally, based on the values from Table 4, the permeability considered for the first region was 1.2616×10^{-9} m^2, for the third region the permeability considered was 5.34693×10^{-10} m^2, which equals the average from the results of Specimen 1 in Table 5.

Appendix B. **Determination of Injection Time**

Introduction

This appendix provides an insight about the process of determining the injection time for the Sensor Nose Cone.

The study of the injection time was undertaken during the process of defining the initial hypothesis. The injection pressure represented the only process parameter for the RTM process, which was impossible to define only using the findings from the literature.

The task of defining the injection pressure can be considered complex. As mentioned in Chapter 2, the pressure gradient caused by the vacuum and injection pressure should have been sufficient to allow the matrix to fill the mould cavity before reaching the gel point, and at the same time to avoid the entrapment of voids.

Therefore, the results gathered from this study helped making the decision for the initial hypothesis of the RTM process.

Method

The method developed to calculate the injection time of the RTM process was based on Eq. 2, in which the mould cavity volume is a constant value extracted from the designed CAD model, and the flow rate is calculated by multiplying the flow speed by the cross sectional area at a certain position.

$$Injection\ Time[s] = \frac{Mould\ Cavity\ volume\ [m^3]}{Flow\ rate\ [m^3/s]} \qquad \text{Eq. 2}$$

When defining the volume of the mould cavity, it was decided not to consider the portion of the volume occupied by the reinforcement material. This decision was made in order to obtain a conservative result from the calculations, because, if the value of the mould cavity volume took into account the volume occupied by the fibres, it would lead to a smaller volume occupied by the resin matrix, thus resulting in a shorter injection time. Hence, the value of the mould cavity volume used for the calculations was 0.002 m^3.

Before solving Eq. 2, it was necessary to determine the flow speed so that the flow rate could have been calculated. To accomplish this, it was used a Finite Element Simulation (FEA) based on Darcy's Law from Eq. 1, in Appendix A. For the simulation, the necessary inputs were the geometry of the laminate, the pressure both at the inlet and at the outlet port, the permeability values in the different sections of the Sensor Nose Cone, and the dynamic viscosity of the resin matrix.

As mentioned in Section 1.2, the laminate of the Sensor Nose Cone was considered to be divided in four regions, each having differences in the laminate staking, which resulted in different permeability values. For that reason, the imported geometry was divided in four regions as shown in Figure 38, and for each region was attributed a specific permeability value. In order to determine the permeability of the Sensor Nose Cone laminate, it was necessary to execute an additional experiment, which is detailed in Appendix A.

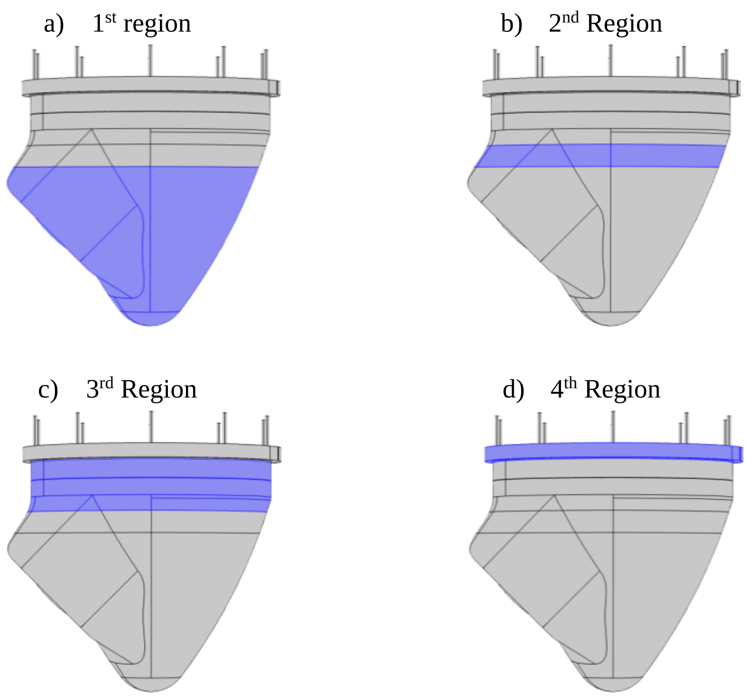

Figure 38 – Sensor Nose Cone model and its regions

The permeability values for each of the sections are displayed in Table 6. The values for the first and third region were established from the study described in Appendix A, but the values for the second and forth region had to be approximated based on assumptions made from the previous values.

Table 6 – Permeability value for each region

Region	Permeability [m^2]
1st Region	1.2616×10^{-9}
2nd Region	8.98148×10^{-10}
3rd Region	5.34693×10^{-10}
4th Region	5.34693×10^{-10}

The second region of the Sensor Nose Cone is characterized by a change in the number of layers, from three to eleven. This caused the appearance of a resin rich area illustrated in Figure 39, which increased the permeability of the laminate. For that reason, it was considered that the second region would have a permeability equal to the mean value between the first and third regions.

For the forth region, despite having a resin rich area close to the outlet ports, the permeability was considered the same as in the third region, because the number of layer was the same in both of them.

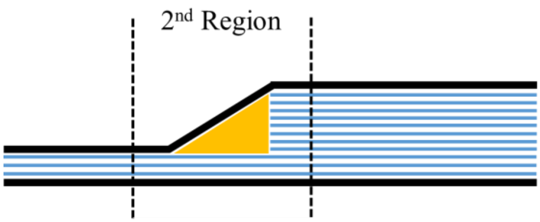

Figure 39 – Representation of the resin reach area in the 2nd region

As described in Section 1.2, the resin system used in this project was constituted by Araldite® LY 1564 and Aradur® 3486 as the hardener, which at room temperature has a dynamic viscosity of 0.3 Pa/s.

In regards to the pressure at the inlet and outlet ports, in order to estimate how the pressure gradient influenced the injection time, it was decided to establish different combinations, which are shown in Table 7. Despite the combinations considered, the difference in the results between the scenarios 1 and 6, and 2 and 7, should be minimal since the scenarios yield similar pressure gradients. As expressed in Eq. 1, the Darcy's Law only uses the pressure gradient, between the inlet and outlet, to determine the flow speed.

Table 7 – Combinations for the inlet and outlet ports

Scenario	Inlet Pressure [Pa]	Outlet Pressure [Pa]
Scenario 1	0	-99 500
Scenario 2	50 000	-99 500
Scenario 3	500 000	-99 500
Scenario 4	500 000	0
Scenario 5	50 000	0
Scenario 6	100 000	0
Scenario 7	150 000	0

In addition to the Sensor Nose Cone simulation, with the intention of ensuring that the results from the simulations would be trustworthy, another two simulations were necessary. These extraordinary simulations were developed to represent the same conditions as the ones for the experiments described in Appendix A, for the first and third regions of the Sensor Nose Cone. The Figure 40 illustrates the model used to simulate the injection time of the third region, which represents an 8.8 millimetre thick laminate with eleven layers. A similar model was used for the first region with the only difference being the thickness, which was 2.4 millimetre corresponding to the three layers. In order to reproduce the same conditions as in the actual experiment, both models had a rectangular shape at the inlet and outlet ports that represented the flow mesh used in the experiment.

Finally, it should be noted that the simulations here presented did not attempt to simulate the flow behaviour of the resin matrix inside the mould cavity, but only to determine the time necessary to fill the mould cavity.

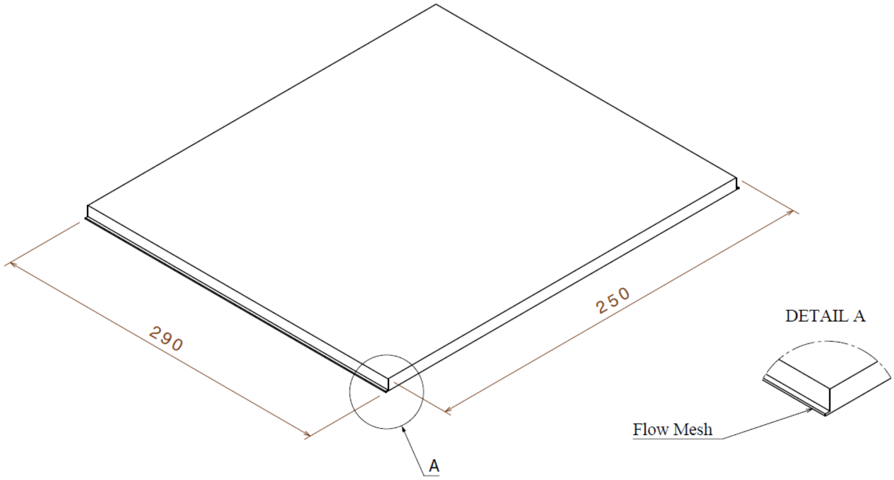

Figure 40 - Model of the specimen for the third region

Results

The results of the simulations representing the experiments in Appendix A and the Sensor Nose Cone scenarios, are shown in Table 8 and Table 9 correspondingly.

Table 8 – Result achieved for the additional simulations, of the 1st and 3rd regions

Scenario	Flow speed at the inlet port [m/s]	Flow rate at the inlet port [m^3/s]	Time for injection [min]
Region 1	0.00275	6.38×10^{-7}	5
Region 3	0.0057713	1.33894×10^{-6}	8

Table 9 – Simulation results of the Sensor Nose Cone for each scenario.

Scenario	Flow speed at the inlet port [m/s]	Flow rate at the inlet port [m^3/s]	Time for injection [min]
1	0.053292	1.04452×10^{-6}	32
2	0.080072	1.56941×10^{-6}	21
3	0.32109	6.29336×10^{-6}	5
4	0.2678	5.24888×10^{-6}	6
5	0.02678	5.24888×10^{-7}	64
6	0.05356	1.04978×10^{-6}	32
7	0.080341	1.57468×10^{-6}	21

Discussion

From the two additional simulations for the first and third region panels, the injection times obtained are considered valid, because the results are very close to the ones of the real experimental tests. The difference are in the range of one to two minutes. Thus, having a simulation matching the experimental results, increased the confidence in the results obtained with the Sensor Nose Cone simulation.

The inlet and outlet pressure values were selected in order to have different combinations with similar pressure gradient, allowing to conclude that results of the simulations would only depend on the gradient and not on the specific values of the pressure in the ports. Meaning that for a simulation with 1.5 bar of pressure at the inlet and 0.5 bar at the outlet would yield the same results as another scenario with 0.5 bar at the inlet and -0.5 bar at the outlet.

The results of the simulation in flow speed are represented in Figure 41 by the changes in colours from red to dark blue, corresponding from faster to slower speeds. The variations in the flow speed were in accordance with a constant flow rate in the Sensor Nose Cone, since the value of the speed was higher in areas with smaller cross sectional area, as is the case of the inlet port.

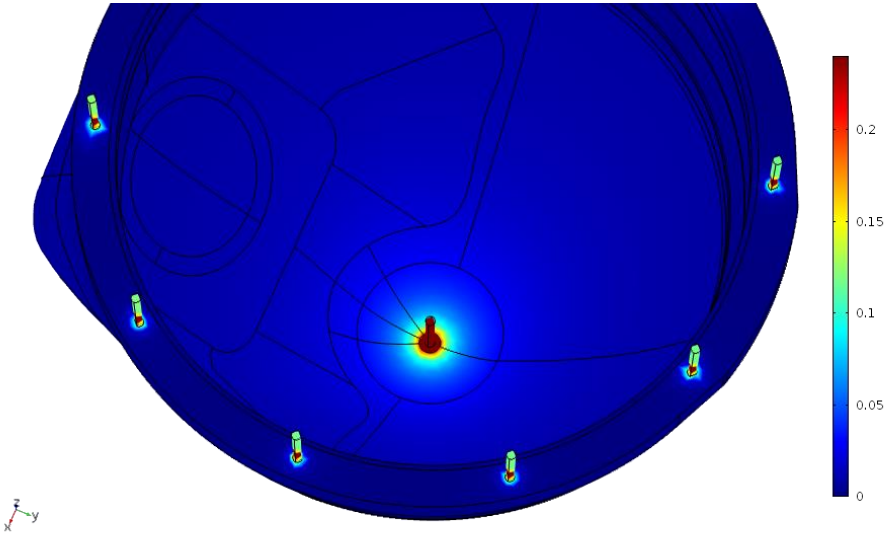

Figure 41 – Image taken from the results of the Sensor Nose Cone injection simulation, showing the flow speed [m/s]

Despite the positive results obtained in this simulation, it should be pointed out that the values of the injection time did not take into account the bleeding time necessary in order to get a clear stream of resin exiting from the outlet ports.

The results from this simulation prove that would be possible to fill the mould cavity using a wide range of pressure gradients without exceeding the pot life of the resin system. Therefore the pot life of the matrix did not represent a constraint for this project.

Appendix C. **Designed Experiments Based on Factorial Design at Two Levels**

Introduction

Learning is a process that can be approached in several ways. As for the purpose of this study, it was decided to change the standard iterative learning process by interrupting the cycle with an intermediate learning process. The advantage of this approach was the possibility to design a simpler experiment, that replicated the true state of nature of the RTM process for the Sensor Nose Cone, and arrange it in such a way so that the results indicated the consequences caused by a change in one of the process parameters.

For that purpose, in this appendix are described the process and results of applying factorial design at two levels for the intermediate learning process in order to study the impact of RTM process parameters, injection pressure, vacuum assistance and hydrostatic pressure.

Method

The first step of this process was to create a simpler experiment that replicated the true state of nature of the RTM process for the Sensor Nose Cone. To meet that requirement, as shown in Figure 42, instead of using the Sensor Nose Cone, the experiments were made using a flat panel. The materials used for the lay-up of the flat panel were composed by 3 layers of eleven inch +/- 45 degrees fibre glass biaxial sleeve as the reinforcement material, with an epoxy matrix constituted by Araldite® LY 1564 and Aradur® 3486 as the hardener. With the purpose of creating the same conditions as the Sensor Nose Cone mould, as described in Sub-section 4.1.1, the sealant used for these experiments was produced in the same way. By doing so the flat panel mould would have the same leakage flaws due to the glued faces of the O-ring, as shown in Figure 43.

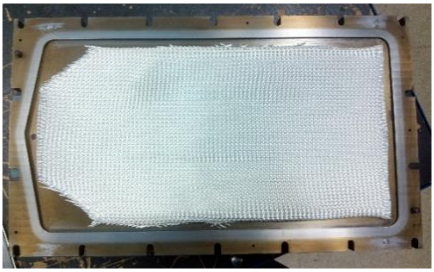

Figure 42 – Flat panel lay-up

Figure 43 – O-ring seal with a purposely made leak

As explained in Sub-section 3.3.1, factorial design at two levels fixes each variable with two versions. Then, the number of experiments depend on the quantity of variables, as a function of 2^n factorial design, n being the number of variables. One of the benefits of this method is the relatively low number of experimental runs to cover all the combinations. Although, with this method each variable is narrowed to two levels, meaning that the entire region of possible values for each variable is limited. Despite that limitation, the factorial design method at two levels is still very useful to express the effect of each variable on a response.

To apply this method to the study of vacuum assistance, injection pressure and hydrostatic pressure it was necessary to define two values for each variable. The values were established using an on or off condition to analyse the effects of using or not that process parameter. The only exception was for the injection pressure parameter, which did not have an off parameter. Instead, it was given a low value. Such had to be done in order to create a pressure gradient for the resin to flow in a scenario that did not use vacuum assistance. In Table 10 are presented the values assigned to each variables together with its symbolic representations. Yet, in Table 11 are presented the eight possible combinations for the experimental runs.

Table 10 – Values assigned to each variable

	Injection pressure [bar]		**Vacuum assistance**		**Hydrostatic pressure [bar]**	
Value	0.5	5	Off	On	0	5
Symbol	-	+	-	+	-	+

Table 11 – Experimental combinations for a 2^3 factorial design

Test Number	**Injection pressure**	**Vacuum assistance**	**Hydrostatic pressure**
1	-	-	-
2	+	-	-
3	-	+	-
4	+	+	-
5	-	-	+
6	+	-	+
7	-	+	+
8	+	+	+

As explained in Sub-section 3.3.2, to evaluate the results from the experiments, instead of using a quantitative based approach and count the number of voids, the panels were evaluated using a qualitative grade system based on visual inspection, which was assisted with a microscope. The grade system used a scale from one to five to classify the results of each experiment, which description follows below:

- Grade 1: is given to a complete failed laminate, meaning that there is a combination of a dry spot and a large quantity of voids.
- Grade 2: is used to describe a laminate without one of the defects, but its quality is still unacceptable.
- Grade 3: classifies a panel with a reasonable quality, which still has a considerable amount of voids.
- Grade 4: describes a panel with almost no voids.
- Grade 5: is given to a panel with no visible voids, and a very low quantity of porosities.

Finally, to facilitate the analysis, as illustrated in Figure 44 the results were used to build a geometric representation of the responses correspondent to changes in the variables.

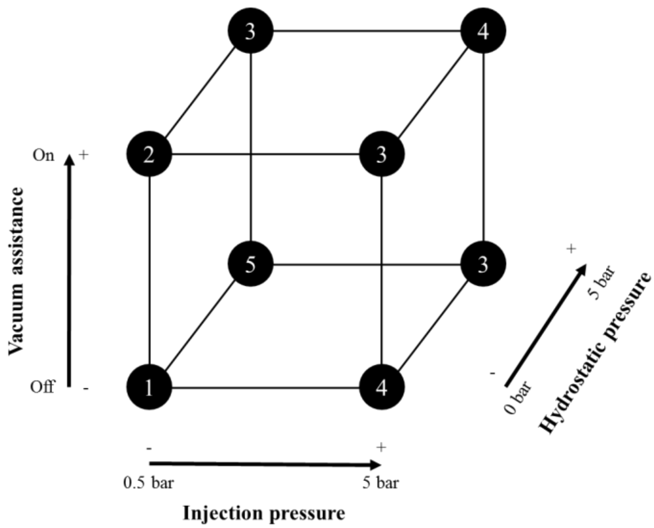

Figure 44 – Example of a geometric representation of the variables behaviour

Results

The grades given for each run are presented in Table 12, as well as the geometrical representation of the response correspondent to changes in variables, displayed in Figure 45.

In the following paragraphs are given justifications to the attributed grades to each test:

- <u>Test 1:</u> was graded with a 2 due to the quantity of voids, and, despite not having a dry spot, from Figure 46 it is visible that there was a large region with a low degree of penetration of the resin.
- <u>Test 2:</u> was graded with a 1, because it had a combination of a large dry spot and a high void content, which is noticeable in Figure 47.
- <u>Test 3:</u> was graded with a 4, because by observing with a microscope with a magnification of 2x, or even at the naked eye, there were no visible voids, Figure 48. It was necessary to use a magnification of 20x, in order to find porosities, Figure 49. The reason for not attributing a 5 to this panel, is justified by the degree of penetration of the resin, because, as illustrated in Figure 50, there were some fibre bundles with a lower wet-out.
- <u>Test 4:</u> was graded with a 1, due to the quantity of voids and to the large dry spot shown in Figure 51.

- Test 5: was graded with a 4, because it contained almost no voids. The only visible ones are illustrated in Figure 52, and these are located outside of the laminate. Another positive outcome from this test was the improved degree of penetration. The argument for not attributing a 5 is explained by the high quantity of porosities, which are shown in Figure 53.
- Test 6: was graded with a 2 because, as displayed in Figure 54 there is a large dry spot in the middle of the laminate, and the fibre lay-up was distorted. Other than that, it must be mentioned that the degree of penetration of the resin is considered very good and had almost no voids, mostly just porosities, as shown in Figure 55.
- Test 7: the maximum grade 5 was given to this test, because the panel had no visible voids and even using the microscope it was possible to see that the quantity of porosities was very low. It is considered that this test provided with the best results.
- Test 8: despite being considered contradictory, due to the dry spot shown in Figure 58, the panel was graded with a 4. Such grade was given because, other than the dry spot, the panel had no visible imperfections. It was considered that it had a good degree of penetration as well as almost no presence of voids, mostly just porosities that were only visible at the microscope level.

Table 12 – Experiment combinations and the corresponding grade

Test Number	**Injection pressure**	**Vacuum assistance**	**Hydrostatic pressure**	**Grade**
1	-	-	-	**2**
2	+	-	-	1
3	-	+	-	4
4	+	+	-	1
5	-	-	+	4
6	+	-	+	2
7	-	+	+	5
8	+	+	+	4

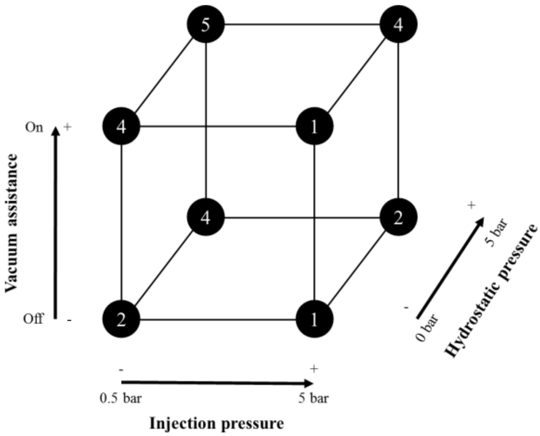

Figure 45 – Geometric representation of the results

Figure 46 – Panel top view of test 1

Figure 47 – Panel top view of test 2

Figure 48 – Microscope view of test 3 with a magnification of 2x

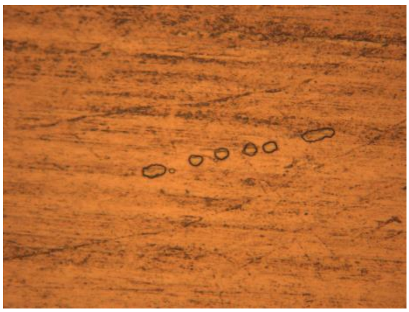

Figure 49 - Microscope view of test 3 with a magnification of 20x

Figure 50 - Panel top view of test 3

Figure 51 - Panel top view of test 4

Figure 52 - Panel top view of test 5

Figure 53 - Microscope view of test 5 with a magnification of 2x

Figure 54 - Panel top view of test 6

Figure 55 - Microscope view of test 6 with a magnification of 2x

Figure 56 - Panel top view of test 7

Figure 57 - Microscope view of test 7 with a magnification of 20x

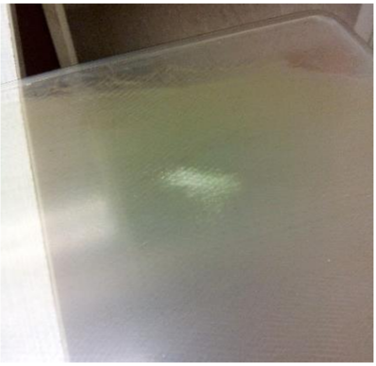

Figure 58 - Panel top view of test 8

Figure 59 - Microscope view of test 8 with a magnification of 2x

Discussion

From the geometric representation of the results, in Figure 45, it is possible to extract several relationships between the variables. By comparing the bottom and top plan, highlighted in Figure 60, it is possible to conclude that using vacuum assistance improves the quality of the laminate. The same can be done using Figure 61, by comparing the left and right plane, from which becomes evident that reducing the injection pressure leads to better results.

Regarding the hydrostatic pressure, it is most effective when using a low pressure gradient, because the risk of dry spots increases in the cases using a high pressure gradient. The results obtained made it evident that the hydrostatic by itself is not enough to compensate the dry areas. A particularly interesting result came from test 5 (-/-/+), which showed that it is possible to obtain good results without using vacuum assistance, when combining a low injection pressure with a high hydrostatic pressure.

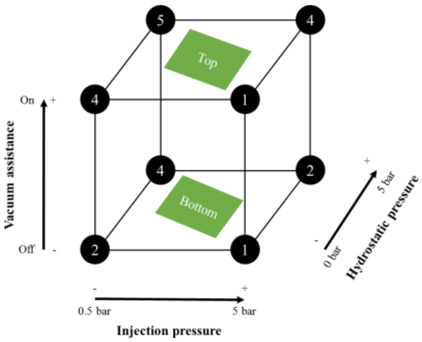

Figure 60 – Top and bottom of the geometrical representation

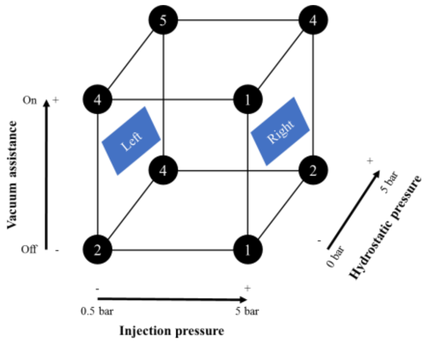

Figure 61 - Left and right of the geometrical representation

With the experiments made it was also possible to realize that even though the sealant had a purposely made leak, it showed no effect on the laminate quality in tests using vacuum assistance. Regarding tests 6 and 8, the cause for the dry spots can be explained as a result of the fibre movement caused by the resin flow, which pushed the fibres towards the outlet port, thus clogging it.

Regarding the method selected to study the three process parameters, the factorial design at two levels performed as expected. As can be seen from Table 12, the fact that no panel was graded with a 3 means that the results only show extreme responses towards the extreme change of variables. Thus, as expected, this method is appropriate to indicate behaviour trends caused by changes in the variables. It must be added that with a wider experimental campaign, would have been possible to obtain a better representation of the reality, since in this study was only possible to perform each test once.

Despite that, it is concluded that the best approach is to use a low injection pressure, combined with vacuum assistance during the injection stage, and a high hydrostatic pressure during curing.