

RTM MOULD DESIGN AND CONSTRUCTION FOR A DN 50 PN 16 FLANSCH

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Hiermit versichere ich, die vorliegende Arbeit selbständig und ausschliesslich mit den angegebenen Hilfsmitteln angefertigt zu haben. Carles Alabau Perich.

Unterschrift:

Carles Alabau Perich.

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1. Introduction

- ❑ Objectives.
- ❑ State of the art.
- ❑ Antecedents.
- ❑ Boundaries of the project.

1.1 Objectives

The objective of this project consists of designing and constructing a RTM mould for a loose flange of glass fibre reinforced plastic (GRP).

The design phase has the mission to realise a quality and simple design of the RTM mould, with the objective to obtain an easy and economic phase of construction and the more possible great characteristics of the loose flange.

In fact this RTM mould will be a mould prototype, which will be developed in the future to obtain an RTM mould able to support a loose flange production. Therefore when more steps are developed in this project, then the future objective will be near.

1.2 State of RTM mould art

It is impossible to underestimate the importance of properly designed and manufactured tooling in composites processing. Even in the case of the relatively simple such as used in autoclave moulding. There are many instances where inadequate tooling was one of the greatest sources of rework in production setting. In most variants of RTM the mould is solely responsible for the geometry and the tolerances of the wanted product. The tooling dictates how the resin will enter and leave, control the filling process and thus the quality of the product. The tool must also react all the loads from mould closure and resin pressure and provide the heat required to cure the resin. The longevity and the cost of the tooling make a major contribution to production economics [P97].

For all these reasons it can be expected that the design of the RTM tooling will be a more complex than tool design for other composites processes. Mould design and product design are linked to each other and to production engineering. RTM tooling approaches must be designed and planned with as much care as that given to the pieces themselves. Equally, piece and mould are heavy interlinked. For example changes in assumed fiber volume, $V_f\%$, can have dramatic effects on mould closure forces. Because of this sensitivity the tool design and piece design processes must proceeded, instead of the piece fully designed before the tooling is considered. Implication in tooling design decisions in the on the potential production engineering approaches should also be considered as they arise and not be left to the end of the design process [P97].

In [P97] the authors experience with the design and operation of RTM tools has covered a wide range of materials, types of tool, clamping, sealing, heating, injection and ejection options, in both development and production environments. This experience has undoubtedly coloured to response some approaches and materials problems, but exist some disagrees, for example, a tooling method which is considered to give good tolerances in one market might be wholly inadequate for another. RTM is still a rapidly expanding field, with new developments coming so rapid that few developments may not always be covered. Lastly, the problems of any component might not have arisen before. Unfortunately, RTM has not been for long enough that standard solutions have been developed to all potential problems. Mould design is very much than a real design task, rather than applications of standards.

1.3 Antecedents.

The present project is included in a study which investigates the mechanical behaviours and the material properties of flange connections like a base to optimize the actual state of the technique.

The investigations are developed in collaboration by the University of Clausthal (PUK), Stuttgart (IMWF) and Magdeburg (LMI).

The development of the described studies will be used for the chemical industries and engineering departments located in services marks. The optimization of seal technologies will benefit the industries which produce the seal products. Therefore the optimization of flange composition and assemblies of glass fibre will contribute to improve these companies, which sometimes are little. These improvements will benefit also the following areas: mineral industries; chemical industries; energy and water logistics.

1.4 Boundaries of the project.

The boundaries of the project include the following points:

- The first part consist of developing the design of the RTM mould with the objective to reach the wanted characteristics of the loose flange and also to adapt the design characteristics with the possibilities of the factory.
- The construction of the RTM mould is made by the factory of the Institute of Polymer Materials and Plastics Processing (PUK). In this part of the project the presence of the designer only consists of supervising the different parts of the mould before proves.
- The last part consist of proving the RTM mould in the factory of the department, with the objective to observe and analyse which aspects of the RTM mould solution work satisfactory and which unsatisfactory. After that try to find the reasons of this bad comportment and correct it.

2. Specifications.

- ❑ Flange connection problems.
- ❑ Flange Requirements.

2.1 Flange connection problems.

Nowadays exist problems in sizing the flange connection of glass fibre, specially with the thickness of this flange connection, which is used in the chemical industries.

Generally the problem is when the forces of bolts are greater, then it is necessary to increase the thickness of the flange connection and also increase the demands of bolts and flange. Therefore the design of flange should focus in the assembly and in particular in the bolts forces, with the target to not exceed the resistance of the flange.

Using flange of glass fibre the range between minimum required and maximum admissible bolts forces is not so much. The experience using flange connection of glass fibre says that the election of standard flange to reach a constancy joint is very difficult without overstressing the flange [MPA06].

Figure 2.1 shows a flange connection of glass fibre [MPA06].

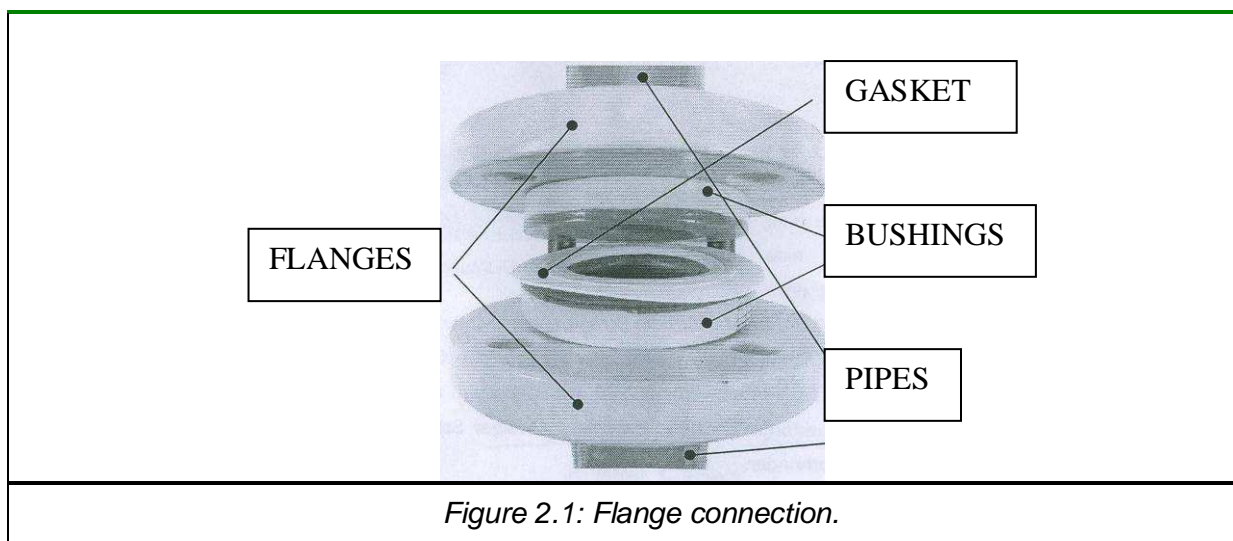


Figure 2.1: Flange connection.

Therefore different projects exist to solve and study these problems of the flange connection, all of them with the objective to optimise the gaskets of glass fibre, the flange and calculation method.

The present project is included in this studies and its target is focused in the flange of the connection, concretely in its production using a RTM mould. In fact, its production using the RTM technique has to solve some difficulties such as the non-homogenous fibre, the air bubbles and the small fibre which decrease the mechanical properties of the loose flange.

2.2 Flange Requirements

DIN 16966 describe the dimensions of pipe joints and their elements of glass fibre reinforced polyester resins; bushings, flanges and gaskets. This norm define a wide range of loose flange and their nominal diameters (DN) move between 25 and 1.000 mm.

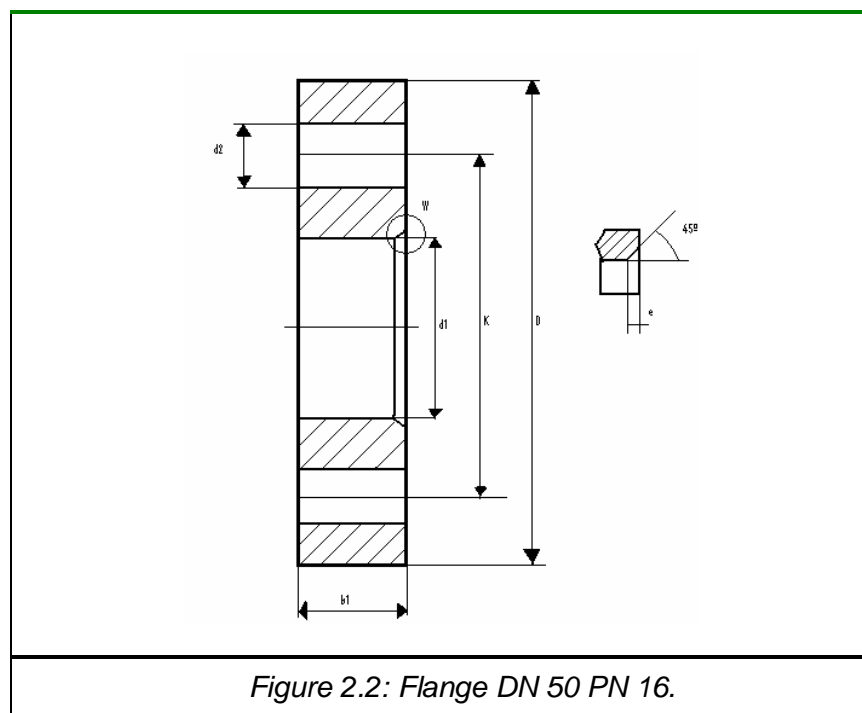
In this project DN50 PN16 flange connection with loose flange is investigated. Table 2.1 describes the different dimensions of this loose flange which is represented in figure 2.2.

Table 2.1 : Flange Dimensions

DIN 16966 / Chapter 6										
<i>DN</i>	<i>PN**</i>	<i>D</i>	<i>d1</i>	<i>d2</i>	<i>k</i>	<i>b1</i>	<i>e</i>	<i>R1</i>	<i>Bolt</i>	
50	16	165	82,50	18	125	18	3,5	3,5	Num.	Thread
		(±1)	(±1)	-	(±1,6)	(0/2)	(0/0,5)	(0/0,5)	4	M16

(*) Dimensions in mm.

(**) PN = overpressure in bar.



3. Preliminary Study of RTM Mould Design

- ❑ Understanding RTM.
- ❑ Permeability Experiments.
- ❑ RTM simulations.

3.1 Understanding RTM

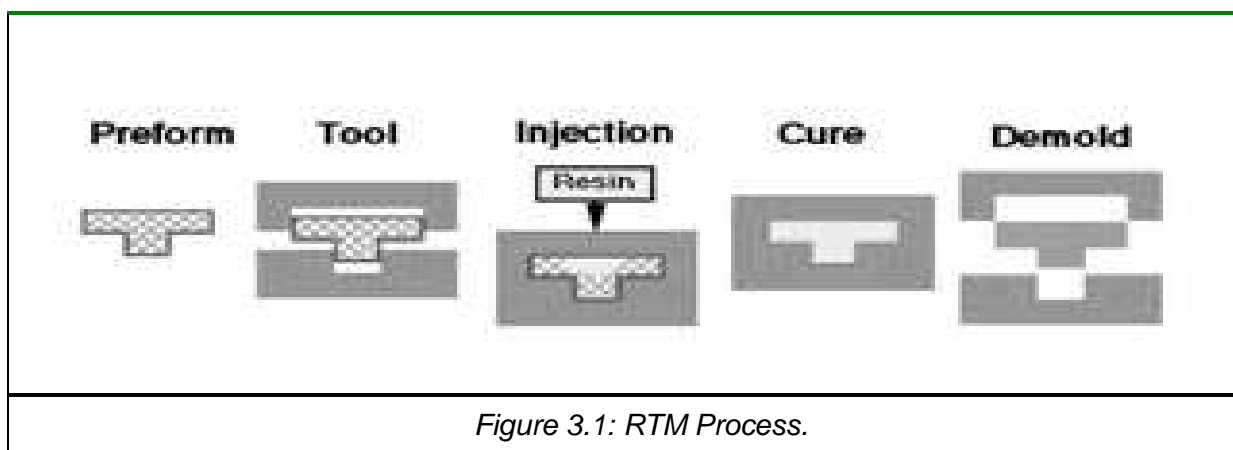
The present point describes the principal basis of the RTM process, based on a literature research [FZR06] and [RKM97], with the objective to understand the posterior developed work and the realized steps.

3.1.1 Definition

The resin transfer moulding process consists of injecting at low pressure a thermosetting resin inside the mould cavity filled with dry fibre reinforcement.

3.1.2 Steps of the RTM process

The RTM process is as follows [Web 5]:



□ Preform

The preform is a fibre reinforcement that is pre-shaped and oriented into skeleton of the actual part. The fibre reinforcement is introduced in the RTM mould cavity.

□ Tool or mould.

The mould must have a cavity that can contain the resin under the injection or transfer pressure. In addition, it needs to have a injection ports and vent ports, and sometimes several.

- ❑ Injection.

The mould is closed and a pre-mixed resin / hardener is pumped under low pressure through the injection ports into the mould cavity. This fluid is known as the matrix material. It must have a low viscosity in order to flow through the fibres of the perform. The air is displaced and escapes from vent ports.

- ❑ Cure reaction.

The resin cure begins during the filling and continues after the filling process. Heat is applied into the mould activates polymerization mechanism, that solidify the resin.

- ❑ The piece is demoulded.

Once the piece is developed sufficiently Green Strength then it is demoulded. Green Strength refers to the strength which is developing during the cure reaction. When the piece comes out of the mould it is still warm, and therefore still reacting. So the green strength is an indicator of how well it holds its shape until its completely cured [P97].

The quality of RTM process depends not only on the fibre reinforcement and resin system, but also on the filling process itself. Therefore it is necessary have a good understanding of the different parameters that take part in the RTM process: materials and filling parameters.

3.1.3 Materials

Two basic materials are used in RTM process: fibre reinforcement and resin.

- ❑ Fibre Reinforcement.

A wide range of reinforcements are available which are suitable for use in the RTM process, including glass fibre, carbon fibre and aramid fibres as well as hybrids. The main factor to select the appropriate reinforcement is the required level of mechanical properties.

- Resin.

Although a wide range of resin systems are available a number of common requirements can be identified for liquid moulding:

- Sufficiently low viscosity to allow complete impregnation.
- Appropriate curing characteristics to provide acceptable cycle times.
- Convenient mechanical properties and physical characteristics to obtain the piece specification.

The typical resins used are polyesters, vinyl esters and epoxies. This resin is dissolved in a reactive hardener, which facilitates the cure reaction between the resin and the hardener.

The most significant limitation on the suitability of a resin system depends on by its viscosity. The range of commercial resin / hardener viscosity is between 0,05 Pa.s and 2 Pa.s.

It is common to mould using a system which contains several additives, which can have a number of effects on the processing characteristics of the resin and the properties of the final composite, such as reduction of surface shrinkage, modified resin viscosity, modified the reaction rate, etc [RKM97].

3.1.4 Permeability

The filling process of Resin Transfer Moulding process (RTM) requires knowledge of the physical properties of the fibrous material. One of the most important properties is the permeability: resistance to the resin flow through the fibre. Permeability depends on the resin and fibre reinforcement.

The resin flows (Newtonian) through a porous medium, as a fibre material, obeys the Darcy equation:

$$q = \frac{-k}{\mu} \cdot \nabla P$$

Where P denotes the pressure field (Pa), K the permeability tensor (m^2), μ the resin viscosity (Pa.s) and q the average volume velocity or Darcy's velocity.

3.1.5 Filling Parameters

The main parameter is the RTM tooling. The tooling in RTM consist of designing the mould. There are a lot of parameters to considerer in the RTM mould design. All of them are developed in this project and some of them are described as follow:

□ Injection Ports.

An injection port provides entry for the resin into the mould cavity. There are infinite strategies to locate this injection port and it always depends on the piece that is to be constructed, so no rule or guide exists to indicate what has to be done in each case.

It specifically depends on the geometry and the dimensions of the piece, as the solution change when the piece is large or short, circular or square, with holes or without, thin or thick, etc. Other aspects are how many ports are necessary and its distribution.

For all these reasons it is necessary to study the filling process, because it is possible to observe the problems and the characteristics of the piece. Nowadays there exist simulation programs that provide the engineers this possibility.

□ Vent Ports.

Since the mould cavity is completely full of resin, vent ports must be made for venting the air out of the cavity. As the resin gets inside the cavity of the mould, the air must be extracted from this space.

There are a lot of possibilities of venting an RTM mould. In any case the vent ports should be made in the last points of the cavity to be full. If the air can not be extracted from this last point the wanted piece will have a defect and this is an important term to study.

- Pressure.

After the resin and the hardener have been mixed the mixture is introduced inside the mould normally with a lower pressure than 6 bars. However, there exist various RTM processes that can be arrived until 200 bar. The most important reasons to work under a low pressure between 1 and 6 bar are that the structure of the fibre does not change during the filling process and the flow front is regular and homogeneous, because the filling velocity is lower. As a result of that, fibres are totally impregnated and the air can be extracted easier, because the air has less time to be evacuated when the filling process is faster.

- Vacuum.

There exist other solutions to introduce the resin inside the mould, as using a vacuum pump. The principle of vacuum injection is that seal mould cavity is created between the vacuum bag and a mould. This cavity is then evacuated which compacts the reinforcement and removes the residual air. Resin is then introduced to the cavity. Vacuum process provides the usual advantages of reduced impregnation times due to a reduction in resin viscosity.

3.2 Permeability Experiments

The enterprises that provide the weave do not know about permeability, because it is an intrinsic property of the fibrous material, and it also depends on which mixture (resin / hardener) will be decided, how many layers will be used and which compression will be between the different layers.

For all this reasons it is ought to be assessed experimentally, although nowadays a standard or exact method to determinate exactly this permeability does not exist. In fact permeability experiments have always been a source of disagreement among investigators of the RTM process.

In this project the permeability of the weave of fibre glass will be measured using the method of Concurrent Permeability Measurement Procedure (CPMP). Nevertheless, it will be described in detail later, the method presents the advantage of providing reliable results with relatively simple equipment.

There are also several experimental data processing which can provide the final permeability. In this project an Excel program is used, which was created by the personal of Institute of Polymer Materials and Plastics Processing (PUK). Even though this subject will not be discussed in this project because it requires much study and is not an objective.

- **What is exactly looked for with this experiment?**

Permeability is one of the most critical parameters in RTM flow simulations. In order to characterize the fibre reinforcement, it is necessary to measure its principals permeability's k_1 , k_2 and k_3 (x , y and z).

However, most of the time k_3 is usually neglected when the thickness is sufficiently small and only planar k_1 and k_2 permeabilities are evaluated. In fact, there exist several experiments to determine the permeability in the z direction, k_3 , but this project does not analyze the Z permeability because the injection port is situated on the lateral of the channel of the flange. This consideration is usual among the RTM investigators and is based on the results of several experiments. The next point is to value the influence of this permeability in flow simulations, and if was necessary realize this experiment. Therefore, these experiments try to find a representative and exact planar permeabilities, k_1 and k_2 , because they are necessary as an input of RTM flow simulation.

3.2.1 Processing Equipment

The instrumentation and the different elements of the concurrent method is as follow:

1. Computer Control.
2. Container of mixture.
3. Pressure Control (Barometer).
4. Injection tube.
5. Plastic cup with mixture (resin / hardener) or oil.
6. Web Cam.
7. Injection point.
8. Mould steel base.
9. Fibre reinforcement.
10. Vent point.
11. Vacuum tube.
12. Container of exit resin.
13. Flow Front

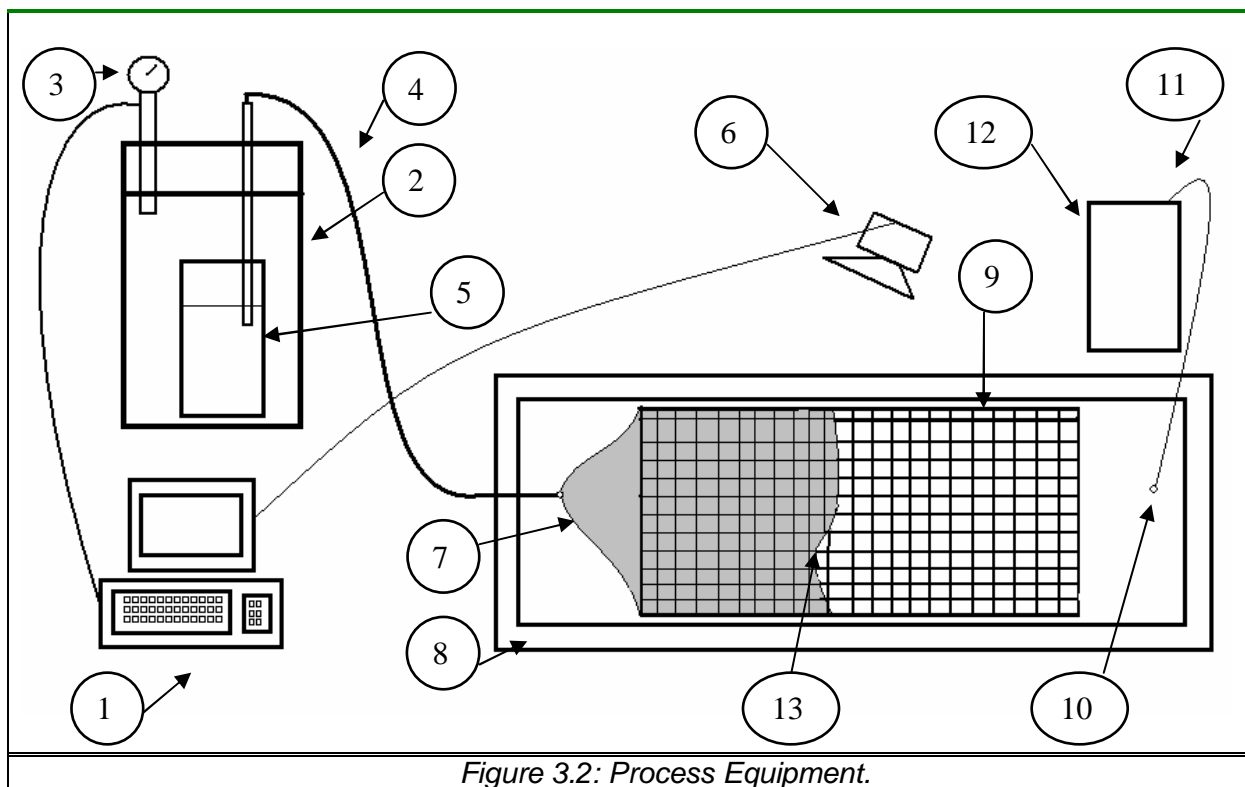


Figure 3.2: Process Equipment.

A part of the previously described instrumentation other secondary instruments are necessary, as gloves of plastic, a knife to cut, a dressing-gown, soap, a sponge, a scale, flanges, a screwdriver, a spatula, a plastic band and a transparent rectangular part of the mould.


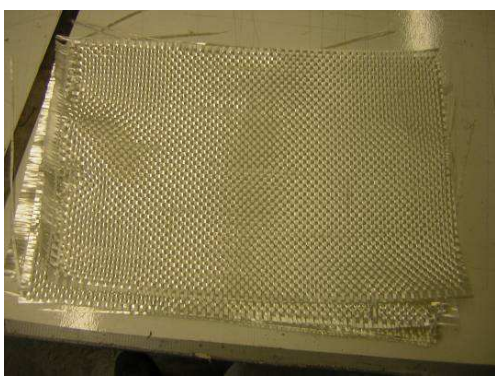
If resin is used for the experiment in additionally the following instruments are necessary: more meters of plastic tube, a dryer, a drill, a paintbrush, an demoulding agent, a spatula and hammer.

3.2.2 Permeability Measurement Method

The principle of method consists of cutting and setting the weave of glass fibre on the rectangular steel mould, with its principal directions aligned with the rectangular mould. The mould is sealed and then fluid is injected with a constant pressure. Vegetable oil and RTM resin are used, because their viscosities are very similar. In fact RTM resin has a viscosity between 30 and 200 (mPa.s). During the injection, the operator can observe the flow front through the weave and, using a web camera, recorder the flow front position. With this recorder it is possible to calculate the time table of the front flow advance and then this table will be used for experimental data processing to calculate the value of permeability.

The permeability measurement is described step by step in the following points:

Table 3.1 : Permeability Method

Step 1	Cutting the weave of glass fibre
<p>The first step is cutting the weave of glass fibres. Normally, glass fibre come from the factory rolled like a cylinder, therefore is necessary to unfold the rolling upon the cutting table, to be cut on the required dimension. A wide variety of weaves design are available, but in this case the plain weave is used, in which weft yarns pass alternately under and over each warp yarn.</p>	
	
<p><i>Figure 3.3: Table to cut.</i></p>	<p><i>Figure 3.4: Used Weave.</i></p>
<p>In the figure 3.3 it can be seen the table where the rolling weave is cut and the figure 3.4 shows the weave with the required dimensions for the permeability experiments. The dimensions of this glass fibre weave are: 40 cm x 25 cm x 0,44 mm (Weight = 600g/m² and thickness = 0,44 mm ; HP – Textiles ; HP – P600E)</p>	
Step 2	Impregnate the superficies of the mould with a demoulding agent.
<p>If the experiment is realized with resin, once the resin has cured it can stick on the surface of the mould, therefore it is necessary to impregnate the surfaces and different parts of mould, to be able to demould the piece and extract all the parts.</p>	

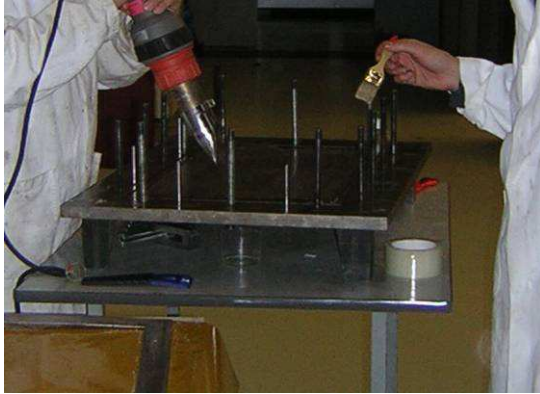


Figure 3.5: Applying demoulding agent



Figure 3.6: Dry the impregnated. Superficies.

The process of impregnation consists of applying five layers of a demoulding agent on the different surfaces which have contact in the mould. Between one impregnation and other impregnation it is necessary to dry the demoulding agent to obtain a sufficient absorption of the product.

Step 3

Place the glass fibre on the mould.

The number of layers to use depends on the wished fraction of glass fibre volume or FGV, therefore this value should be calculated before the experiment. For example in the experiments 4 layers are used, so the GFV is as follows:

$$GFV = \frac{N \cdot W_{weave}}{t \cdot N \cdot \rho_{glassfibre}} = \frac{4 \cdot 0,6 (kg / m^2)}{0,002 (m) \cdot 2.500 (kg / m^3)} = 0,48 \approx 48,00\% \text{ of glass fiber}$$

The rest of volume is the fraction of resin (52,00%). In this case the value of $t \cdot N$ is the thickness of the cavity between the upper and lower part of the experiment. The normal range of values of GFV is between 40% and 55%. If GFV is lower than 40% the mechanical properties of the laminate provided by the glass fibre becomes comparatively small.

At this moment is possible to place strips of rubber all around the fibre preform, injection point and vent point, with the objective to direct the resin or vegetable oil from the injection point to the vent point through the glass fibre, as it can be seen in the figure 3.7 and 3.8.



Figure 3.7: Strips of rubber

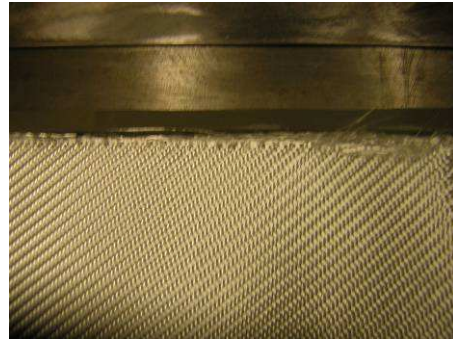


Figure 3.8: Around the fibre preform .

Another aspect to considerate is that sometimes a gap between fibre preform and the rubber strips exist, because it is difficult to cut the fibre preform precisely so the “edge effect” occurs, the same concept that exist between fibre preform and the mould in the real RTM process.

Step 4

Assembly and close the mould.

The assembly consists of placing the superior part of the mould upon the fibre preform and the gags around the mould to realise the closing pressure. In order to observe the evolution of the fluid through the fibre preform a transparent superior part of the mould is necessary.

The pressure is made screwing the gags with the screws united on the inferior part of the mould. The screwing operation is made in two phases, which depends on the moment of torsion. The first moment applied is 30 Nm, in each one of the nuts, and the second applied is 80 Nm, also in each nut.

Step 5	Connections.
<p>The experiment has an entrance connection of the mixture (resin / hardener) and the exit connexion of the resin. The first connection is between the container of mixture and the injection point on the mould. The union is make with a plastic tube, which is connected in the inferior part of the mould.</p>	
Step 6	The mixture.
<p>Once all instruments are prepared one can prepare the mixture between the resin and the hardener, because trying to do this step before does not make any sense. The reason is that normally producers and engineers try to use the fastest hardeners to reach the fastest reaction, with the objective to obtain an efficient RTM process. The consequence is that mixture reacts while the operator prepares the experiment, therefore the resin is lost. The mixture is formed for 100 grams of epoxy resin and 30 grams of hardener. After the mixture is prepared, it is introduced in the container where pumping the resin towards the mould. In all the experiments a constant pressure of 1,5 bars is used.</p>	
Step 7	Initialize the injection process.
<p>Before beginning the injection it is necessary to initiate two software programs in the computer control:</p> <ul style="list-style-type: none"> • <i>DASYLab 7.0</i> : software tool for data acquisition and evaluation. In this experiments the program only governs the injection pressure from the container of mixture. • <i>Creative Webcam center</i> : which registers the recording of the webcam. The camera is hung on the bench which is situated upon the mould. <p>The webcam is used to record the advance of flow front, for this reason a transparent part of mould is used.</p>	

- **Accumulated Experiences in the experiments**

This point has the objective to list the principal mistakes made during these described experiments, to determinate the causes and the consequence on the process.

Table 3.2 : Mistakes during the experiments

<ul style="list-style-type: none"> ❑ Lack of oil. 	<p>One of the problems that can happen is that oil is exhausted before completing the impregnation of the fibre preform. This aspect can be observed easy when air bubbles come into the cavity of the mould, because the process continue pumping, although liquid does not exist, so the process pumps air. Therefore the control of the oil level before beginning each experiment is necessary.</p>
<ul style="list-style-type: none"> ❑ Insufficient pressure to close the mould. 	<p>This can happen when the worker wants to make this step quickly, without comprove the good union of the mould or without knowing the necessary force with which is necessary to screw. The principal consequence is that the flow can escape of the route marked for the strips of rubber, therefore the fibre reinforcement is not impregnated.</p>
<ul style="list-style-type: none"> ❑ Bad positioning of the plastic strips. 	<p>The function of these strips is to conduct the flow fluid for the wished way. As it has been explained, when the mould is closed the plastic strips expand. At this point two typical errors appear:</p> <ol style="list-style-type: none"> 1. The injection point become closed, that is due to placing to much strips behind the hole, which expands and disturbs the fluid entrance. 2. Lateral edges are created between the dry fibre preform and the expanded strips of plastics, which is called the “edge effect”. This effect create a lateral fluid flow that disturbs the flow front advancing through the fibre preform.
<ul style="list-style-type: none"> ❑ Reference points. 	<p>The points of reference are used to measure the time of advance of the fluid front through the fibre preform. The points are situated under the transparent part of the mould to be differentiated in the video recorder for the web cam. Therefore it is absolutely important that these points can be seen clearly in the recorder.</p>

3.2.4 Data Processing

Once the recording of the filling process is obtained it is possible to start the processing in order to find the permeability.

Two different steps should be made:

- The first step has the objective to get a table with the values of the advancing time of the fluid front through the fibre preform or, in other words, the advancing velocity of the flow front.
- The second step consists of introducing these values in a prepared Excel Sheet, which calculates the value of the wished permeability.

3.2.4.1 Time Table of the flow front advance

Using a simple, but practical, Matlab program makes it possible to transfer the filling process recorder of the fibre preform from the web cam to an interface, that permits dividing the fibre preform in pieces or lines, using points of reference. For each one of these pieces, or lines, the advance time can be calculated. In this project this method is used, but several methods can be also used.

Basically it consists of drawing a rectangle on the video, which fits with the perimeter of the fibre preform. To draw more exactly the rectangle, it is necessary to have references. These references are the little paper points or reference points, which are stucked under the transparent superior part of the mould.

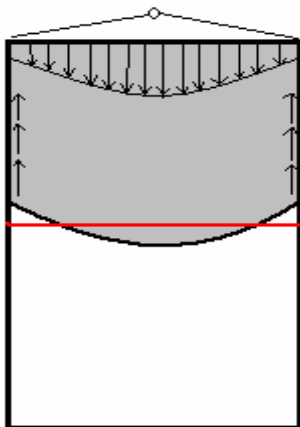
The next step consists of dividing the rectangle. The number of divisions is chosen subjectively. Normally 15 divisions are enough. The more divisions there are, the more exact it is.

In the final step the video is switched on. When oil or resin begins to impregnate the fibre preform, it is possible to write the time that the video gives and it assumes this time as the “0 time” of the table. After that, it is only necessary to write down the time when the flow front arrives at the following line, that until arriving at the end line of the rectangle, or the same, the preform.

But using this method one aspect is important to consider and this is when the arrival of the flow front at one line of the rectangle is considered, because the flow front is not always linear and continuous, exist ascents and slopes of the flow front exist, so: which time has to be measured ?. This method is simple and for this reason can not result all the cases exactly and is based on the coherent consideration that a perfect experiment has to give a homogenous flow front, a “ideal” consideration, because the same resin pressure is introduced through a homogeneous fibre preform, but in reality a lot of aspects affect the experiment, as: sometimes the fibre is not completely homogeneous, “edge effect” exists, the pressure is not the same, etc. So finally it is necessary to consider an average.

So with this it is possible to make some mistakes in this point, but it is a little error compared to the experiment and the global objective of the process.

In order to understand the explication the following drawings can be observed:



In figure 3.9 it is possible to observe the typical case where a flow front delay is produced. Two reasons are present, first the injection point is in the centre, therefore a pressure distribution as the picture appears and the second, is that the expanded plastic strips interfere on the advance of flow front, and therefore it produces a resistance.

The red line indicates the considered average when the flow front surpasses one line of the rectangle.

Figure 3.9: Flow advance 1.

In figure 3.10 it is possible to observe the case of “edge effect”. A principal fluid appears in the two laterals of the fibre preform, because a little way exist between the plastic strips and the fibre preform.

The “edge effect” appears when the preparation of the experiment is not sufficiently correct (pressure, strips, etc).

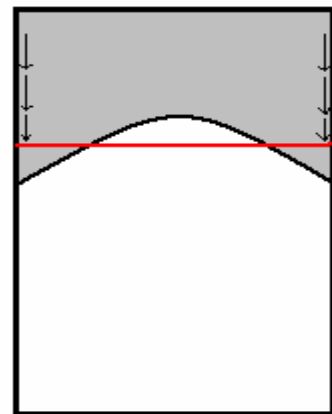


Figure 3.10: Flow advance 2.

Other cases are showing below:

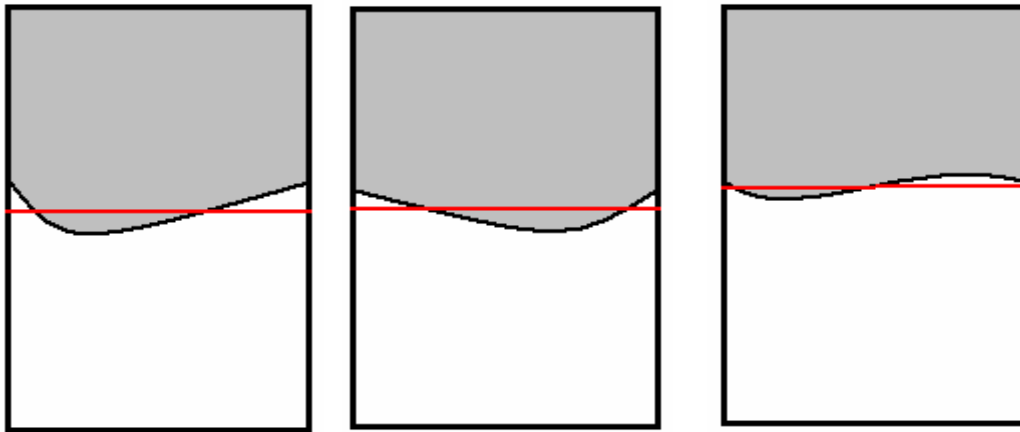


Figure 3.11: Flow advance 3.

Another possible solution if a not very unstable fluid happens, is to try to divide the flow front, in the necessary parts, to be able to consider a homogenous flow front, as the figure 3.16. This method is approximated and it has been applied in the experiment with resin, although it is normally neglected.



Figure 3.12 represents the described case, in which the flow front is divided in two parts for a green line. The red line still represents the average value of the flow front advance.

After calculating the permeability of the both flow fronts and one select the lowest permeability, which is restrictive permeability for the RTM process.

Figure 3.12: Flow advance 4.

It is possible, in fact in this project it has happened, that the flow front is totally unstable and the consequence is that it is impossible to identify an average value of the flow front. Therefore this experiment becomes invalid.

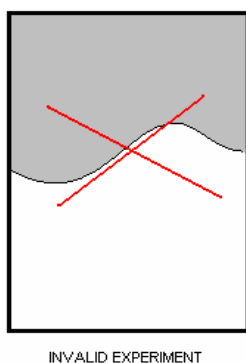


Figure 3.13: Flow advance 5.

The time tables calculate in this project are given as follows:

Table 3.3: Time Tables of the flow front advance / Permeability Experiments			
Experiment 2 (oil)		Experiment 3 (oil)	
Line Number	Time Advance	Line Number	Time Advance
0	65,40	0	26
1	67,00	1	27,20
2	69,20	2	28,40
3	71,80	3	29,80
4	74,20	4	31,20
5	76,60	5	33,60
6	79,80	6	35,60
7	83,80	7	37,20
8	91,60	8	39,80
9	101,00	9	45,60
10	105,40	10	48,40
11	110,20	11	51,20
12	114,60		
Units	Seconds	Units	Seconds

The pressure of these experiments have a constant value of 1'02 bar.

The experiment number 1 becomes invalid, because the flow front is total unstable.

Table 3.4: Time Tables of the flow front advance / Permeability Experiments

Experiment 4.1 (resin)		Experiment 4.2 (resin)	
Line Number	Time Advance	Line Number	Time Advance
0	70,44	0	72,00
1	75,80	1	77,60
2	80,00	2	83,60
3	85,60	3	89,20
4	90,80	4	93,40
5	103,20	5	102,20
6	110,00	6	111,20
7	115,00	7	122,40
8	123,50	8	132,60
9	142,60	9	140,80
10	155,4	10	157,00
11	168,00	11	169,20
12	182,00	12	182,00
13	195,20	13	198,20
14	206,4440	14	216,20
15	222,440	15	241,00
16	237,20	16	264,80
17	253,20	17	287,00
18	265,80		
19	289,20		
20	318,80		
21	347,40		
<i>Units</i>	<i>Seconds</i>	<i>Units</i>	<i>Seconds</i>

The flow front of the experiment with resin is divide in two parts as a solution of a unstable flow front (look figure 3.12).

3.2.4.2 Excel Sheet

When the filling time table is obtained it is necessary to introduce this table into the excel sheet. In fact the excel sheet is based on *Darcy's law*.

Because Darcy's law is composed for more parameters it is also necessary to introduce the following values, which are used in the RTM experiments:

Table 3.5: Used Processing Required

Preform Dimensions		Fibre Characteristics	
<i>Length (m)</i>	0,40 (m)	<i>Density (Kg/ m³).</i>	2.500 (Kg / m3)
<i>Width (m)</i>	0,25 (m)	<i>Weight (kg / m2)</i>	0,6 (kg / m2)
<i>Heigth (m)</i>	0,00044 (m)	<i>Number of layers</i>	4 layers.
Fluid Characteristics		Process Characteristics	
<i>Type of fluid.</i>	Oil or Resin.	<i>Pressure Difference (Pa)</i>	102.000
<i>Viscosity (Pa s)</i>	0,06 (Pa s).		

It can be observed that from all the introduced values in the excel program, only one parameter of the *Darcy's law* leaks: the permeability.

$$\boxed{q = \frac{-k}{\mu} \cdot \nabla P} \text{ and } \boxed{v = \frac{q}{\phi}} \text{ therefore } \boxed{v = \frac{-k}{\mu \cdot \phi} \cdot \nabla P}$$

Where P denotes the pressure field (Pa), K the permeability tensor (m^2), μ the resin viscosity (Pa.s), V the flow front velocity (m/s), q the average volume velocity and ϕ the porosity.

In *Darcy's formula* it is possible to observe why the time table of the flow front advance has been obtained previously. The reason is that the time table provides the flow front velocity, so one of the variables of the *darcy's law*.

As a part of the permeability, the program calculates an interesting intermediate value, it calls: *fibreglass volume fraction*. In fact fibreglass volume is the percentage of fibre inside the fibre preform volume, so is just the inverse value of the porosity, the percentage of air inside the fibre preform volume.

The fibre volume can be calculated from the fibreglass density and the weight of the layers, is calculated as:

$$\boxed{GFV = \frac{W_{total}}{\rho_{total} \cdot d_{total}} = \frac{W \cdot n}{\rho \cdot d_{total}}}$$

Where:

- GFV: *fibreglass volume (%)*.
- Wtotal: *total or equivalent weight (kg / m2)*.
- ρ_{total} : *total or equivalent density (kg / m3)*.
- d total: *thickness of the cavity measured between the upper and lower part of the experiment, therefore where the glass fibre is tablet (m)*.
- W: *layer weight (kg / m2)*.
- ρ : *layer density (kg / m3)*.
- n: *number of layers*.

Therefore the porosity or, the same, the percentage of air in the fibre preform can be calculated as follows:

$$\phi = 1 - GFV$$

Where:

- ϕ : porosity (%).
- GFV: fibreglass volume (%).

Example:

In the following example the fibreglass volume and the porosity of the experiment of this project is calculated, as:

Glass fibre volume:

$$GFV = \frac{W \cdot n}{\rho \cdot d \cdot n} = \frac{0,6(kg / m^2) \cdot 4}{2500(kg / m^3) \cdot 0,002(m)} = \frac{2,4(kg / m^2)}{5(kg / m^2)} = 0,48 = 48,00\% \text{ fiber}$$

Porosity:

$$\phi = 1 - 0,48 = 0,52 = 52,00\% \text{ air}$$

3.2.5 Results and discussions

In the present project, first and after that it was possible to realise the convenient permeability experiments.

Concretely, four experiments were made:

- Three experiments using: *vegetable oil* or *supermarket oil*.
- One experiment using: *epoxy resin*.

From these experiments the following results have been obtained:

Table 3.6 : Permeability experiments / Results with oil

Permeability	
Experiment Number	m ²
1	-
2	1,05 E -10
3	1,50 E -10

Table 3.7 : Permeability experiments / Results with resin

Permeability	
Experiment Number	m ²
4.1	5,84 E -11
4.2	6,32 E -11

The first point to comment is that the permeability values are included in the same rank of values, between 5,8 E –11 and 1,5 E –10 m².

Additionally the excel program provides a representative evolution graph of the permeability through the fibre preform for each experiment. These graphs allow to value more exactly each experiment.

The graph represents the calculated permeability by the excel program for each time value of the front advance time tables. In fact, these graphs describe two different permeability values for each point, the *local permeability* and the *global permeability*. Each value of the *local permeability* considers the previously value of time tables, so it considers always the previous permeability calculated (Example: V1 refers to V0, V2 refers to V1, V3 refers to V2,etc.) , instead of the *global permeability* that considers the calculation referring to the offset (V1 refers V0, V2 refers V0, V3 refers V0,etc.). In this project the local permeability is considered.

- **Oil Graphics**

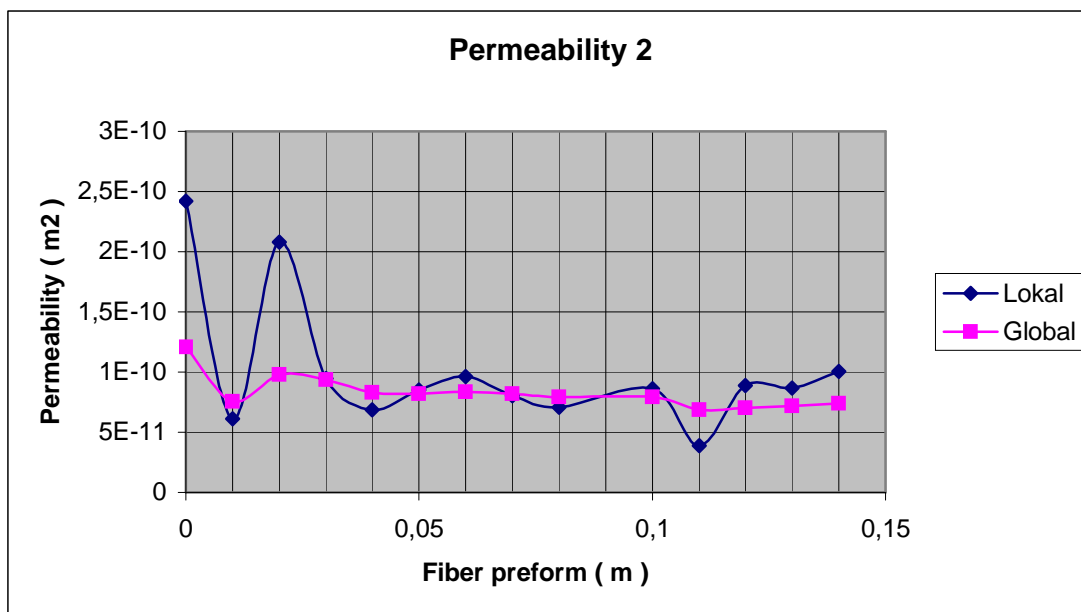


Figure 3.14: Oil Graphic 1.

The figure 3.14 shows that the first points of the *lokal permeability* are different and in the graph of the *global permeability* all the points are very similar. Therefore the global permeability indicates a similar and continuous permeability through the fibre preform, so an indication of a good experiment. The main reason is that the different values of V0, V1,V2, etc., are very similar. Although it is necessary to analyse the lokal permeability accurately. The blue curve represents the *lokal permeability*. The first points have a rang of variation between $2,5E-10 \text{ m}^2$ and $5E-11 \text{ m}^2$, which is not so precisely. Although the local curve becomes stable ($1E-10 \text{ m}^2$) from the three permeability value.

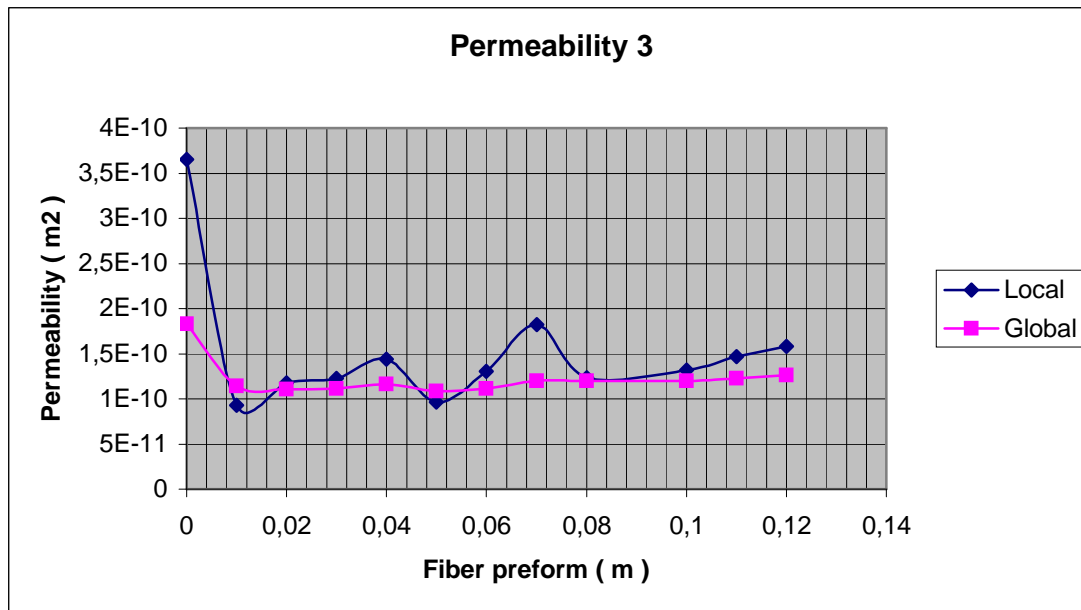


Figure 3.15: Oil Graphic 2.

The X axis represents the length of the fibre preform in m. It is possible to observe that the length of values does not reach the longitude of 40 cm, which is the total length of the fibre preform. The reason is that in some cases, and in this project happens, less length or points to consider does not affect the representative permeability. Therefore the number of points and the length is variable in function of the consideration of each experiment. For example with it has been found that a length between 10 and 15 cm and number of divisions or number of points between 10 and 20 is representative.

The Y axis represents the permeability in m². The rank of values variant between 0 and 4E-10 m².

In the graphs 2 and 3 it is possible to observe the difference between the two curves, but as it has been explained, the permeability value, used in this project, is the average of the *local curve*.

An important aspect to observe is that in the first points of the preform the permeability is elevated and soon it comes more or less stable. The reason of this behaviour is that firstly the pressure pushes the oil from the mould to the fibre preform without resistance and the consequence is that the oil goes inside the first fibres quickly, as the fibre preform realises any resistance against the flow or, the same, has a elevated permeability. The permeability is calculated by each point of the flow front advance, therefore the graphic is initially a curve. After that, the fibre preform becomes more and more impregnated, but the flow advance becomes slower or the same, has more resistance, so more permeability.

Local permeability 2 and 3 becomes stable with $1,05 \text{ E-}10$ and $1,50 \text{ E-}10 \text{ m}^2$ respectively. Therefore is possible to think that the experiments are coherent, the way to find this values is correct and the values are correct, because the values are very similar or have the same order.

- **Resin Graphics**

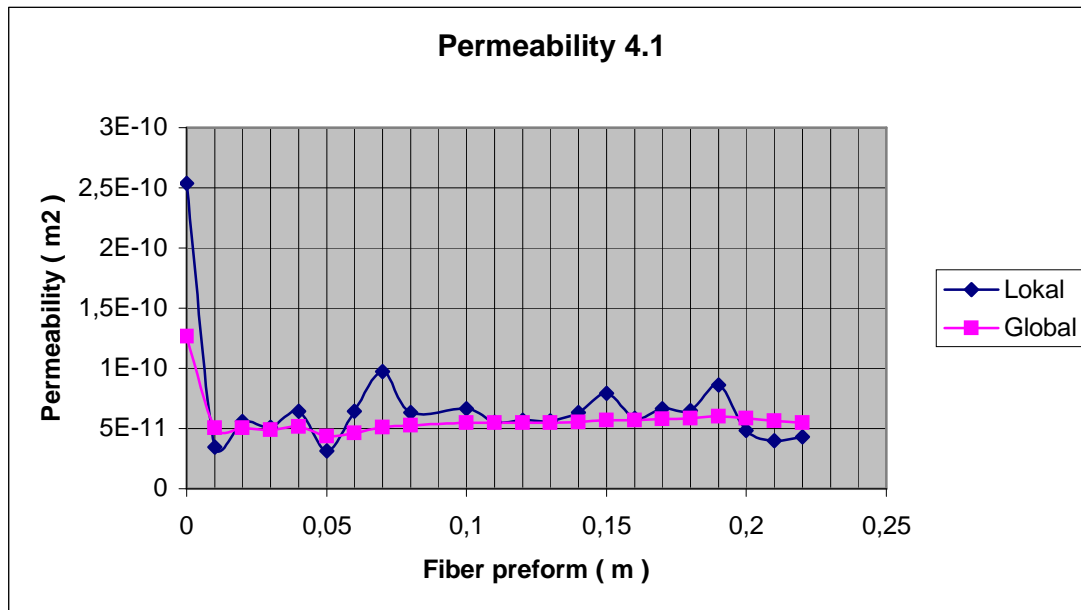


Figure 3.16: Resin Graphic.

With resin, it has been considered that a length between 15 and 20 cm and number of divisions or number of points between 15 and 20 is sufficiently representative. Additionally the experiments using resin are expensive and require more time, so it must be described in detail.

It has been explained that the resin experiment is divided in two flow fronts, therefore there are two permeability results. If the difference between the two flow fronts is important, the permeability values are not so much different, because the rank of values is between $5 \text{ E} -11$ and $7 \text{ E} - 11 \text{ m}^2$, so they are of the same order. In addition, if is necessary use one of this two permeability values, it must always select the bigger one, because it is the security case.

It is necessary to remember that because the viscosity of RTM low viscosity resin and oil is similar, it is possible to compare the values of permeability. There are only a one order difference (multiply or divide 10) between the permeability values using resin or oil. And now is possible to ask: is this difference important ?. It depends on the influence of the

permeability in the RTM simulation of the flange. The response will be described in the simulation point.

Finally permeability values in the literature has been consulted and all values have the same order, using resin, (order $E - 11$). Also colleagues with more experience in the permeability experiments has been asked about the results of this project and all indicate that the values found are coherent.

3.2.6 Conclusion of the experiments

The advantages and disadvantages of the permeability experiments are described as follows:

- **Advantages**

- The method uses cheap and simple materials and it allows to realise experiments with resin or with oil.
- When sunflower oil is used as the fluid of the experiment, the following characteristics are obtained: similar viscosity with RTM low viscosity resin, cheaper than resin, higher number of experiments, oil does not react and is therefore easy to clean.
- When resin is used, the following characteristics are obtained: it is possible to observe the cure reaction and exact behaviour.
- The experiment is simple to carry out and also allows to obtain a sufficient and adequate permeability value for this project.
- The excel sheet, which calculates the permeability value, is simple to use and it provides a coherent permeability value.

- **Disadvantages**

- The method requires enough time to assembly, disassembly and clean.
- As all experimental methods, this method has assembly imperfections, which can influence the final value.
- When sunflower oil is used as the fluid of the experiment, the following characteristics are obtained: it is only a substituted material, so no exact properties.
- When resin is used, the following characteristics are obtained: expensive, low number of experiments, elevated time reaction, elevated temperature and difficult to clean.
- The process to divide the fibre preform to obtain the front time table depends on the investigator (objective), therefore errors occur.

Maybe investigators who are trims in permeability studies consider that many considerations of these experiments are not exact, but on the other side it is possible to think that the importance of the considerations depend on the effect or changes in the objectives, and for the objectives of this project the used considerations are coherent.

3.3 RTM Simulations

3.3.1 Why simulation?

Simulation software has been developed in the last few years to assist the design of RTM moulds. It is more economic to perform simulations before construction of the mould than to modify an existing mould. The mould is the more complex, the more costly are mistakes in mould design. This is the reason why, it is useful to perform a preliminary study by simulation.

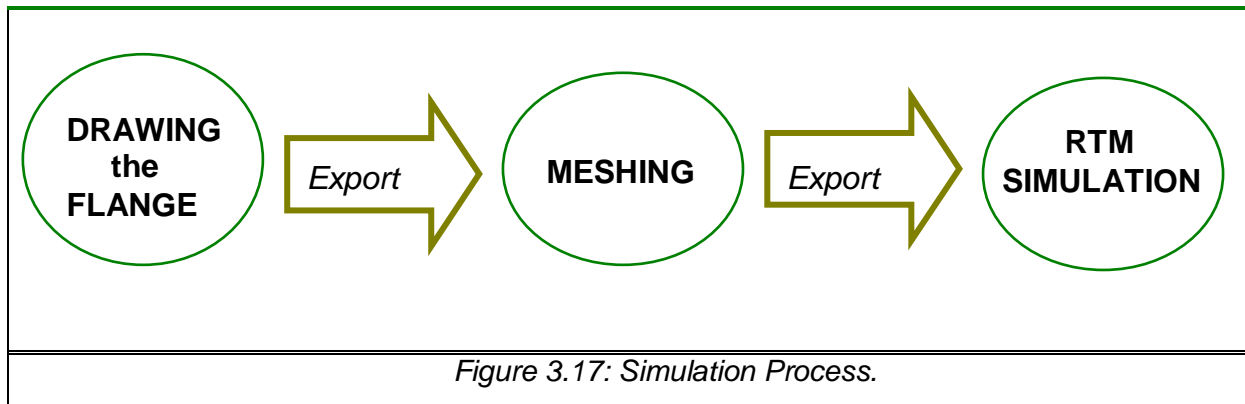
Additionally, in numerous situations, numerical simulations of mould filling can help to avoid problems such as resin rich areas, air bubbles, zones of high porosity, etc. It is also necessary to select a good configuration of injection ports and vents to avoid dry spots and minimize filling time. This is precisely the objective of numerical simulation.

3.3.2 The simulation process

The used simulation software is PAM-RTM by ESI GROUP. This simulation program offers the following options:

- Evaluate various injection strategies before making the mould;
- Visualize the advance of the resin front in the cavity to prevent filling problems such as dry spots;
- Optimize the positions of injection points and vents;
- Visualize the pressure distribution during mould filling;
- Predict the temperature evolution inside the mould cavity;
- Predict the cycle time;
- Analyse the effect of moulding parameters such as resin viscosity, injection pressure and injection rate;
- Analyse the effects of change in geometry, fiber content, reinforcement and resin properties.

PAM-RTM also offers the possibility to insert sensors, to control during the calculation the trends of various parameters involved in the filling process, like the temperature and the pressure.



The simulation process includes the following steps:

- Drawing.

The geometry of the flange is drawn using PRO/E while the “*fluid help channel*”, which provide a homogeneous filling process as is possible to see in RTM simulations, is created using ANSYS.

- Meshing.

The mesh has a big importance in the RTM simulation, because a good meshing means a good representation of the flange, but a bad mesh causes always errors in the flow simulation.

GEOMESH is the program that meshes automatically the imported geometry.

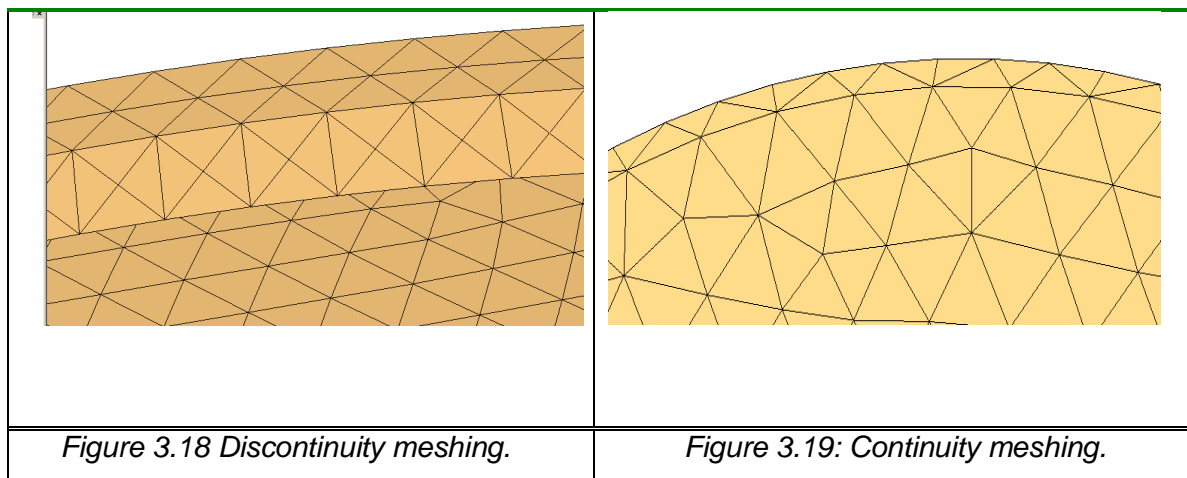
After drawing the geometry is imported from PRO/E to GEOMESH software as an Initial Graphics Exchange Specification (IGES).

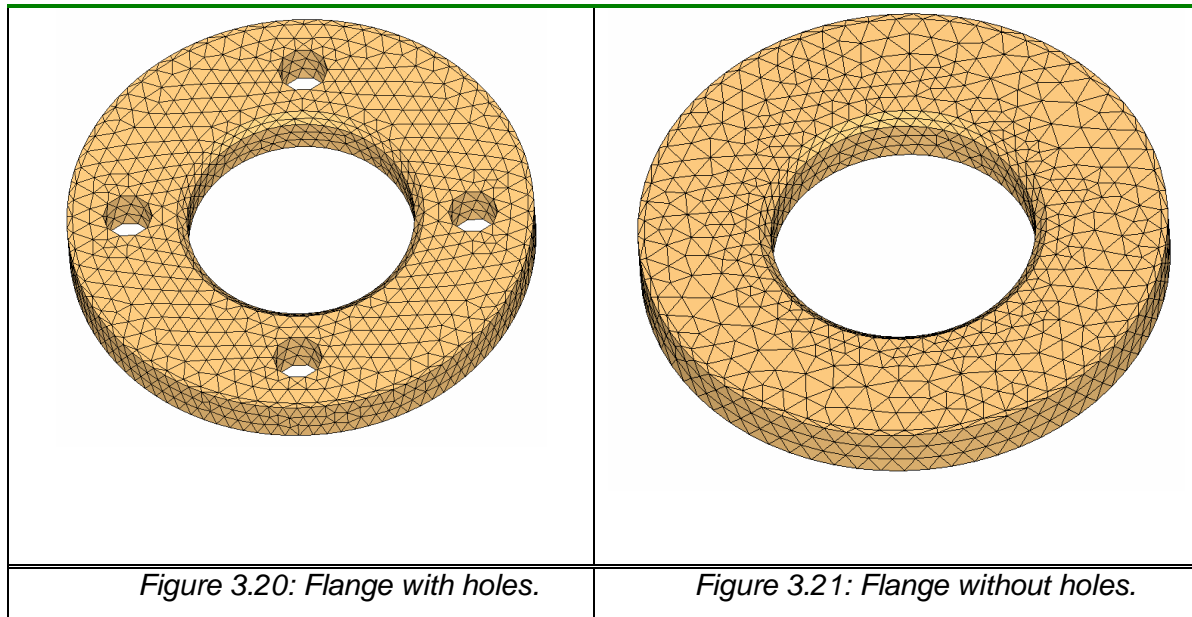
The main problems of the mesh is in the union between different pieces and in complicated geometries like holes.

The figure 3.18 shows the no continuity meshing between two pieces, the flange and the fluid help channel. In this case the problem is that with certain drawing programs GEOMESH does not make a good meshing of the union between two pieces. With the experience it is possible to know which drawing program can be used and which not. In this case using ANSYS for the fluid help channel and PROE for the flange it is possible to find a good meshing of the union, as it can be seen in figure 3.19. In fact, ANSYS pre-processor is considered the best to mesh with GEOMESH, but the PROE allows more flexibility to drawn the 3D model of the flange.

In the figure 3.20 it is possible to observe the flange with holes and in the figure 3.21 the flange without holes. The difference is that the complexity of the meshing increases with the appearance of the holes. A consequence is that a badly representation of the holes appears.

To solve this problem different meshing must be proved until finding one correct meshing, but a “correct meshing” can not only be realised with a lot of nodes, also is a balance between the number of nodes, a good continuity of the meshing and a calculation time of the program not very long must be found.





- Simulating.

After making the meshing it is possible to begin simulating the different strategies of the RTM injection.

The first priority is to find a quality filling process, without defects, as good as it is possible.

An important aspect to observe is which variables intervene in the filling process of the mould, and therefore, which parameters must be analyzed. All these are variables of the RTM process and the geometry of the flange.

These variables can be seen in the following table:

Table 3.8 : RTM simulations / Injection Strategies			
Variables			
Injection Pressure	Permeability	Viscosity of the resin	Porosity
Vent Ports	Vacuum Pressure	Channel to help the fluid	Geometry

Instead of using a determinate method to obtain the strategy of injection, the used method consist in “playing” and modifying the described variables in the simulation to observe what it happens with the results. For this reason, continuously the effects of each variable on the filling process will be described.

3.3.3 The effects of the RTM variables

For describing each effect the used process is based on obtaining a table of results and observing the filling process. The table of results includes the number of nodes and elements of the meshing, the filling time, the simulation time, the injected volume and the lost volume. For each table of results is also necessary to describe which strategy of injection is used, because that allows to determinate which is the best strategy.

□ *Meshing Influence.*

As it has been said the meshing has a big importance to obtain a good simulation, although it is not a variable of RTM process. But how many nodes and elements are needed for a representative simulation of the flange? Or, which quality of meshing is needed?.

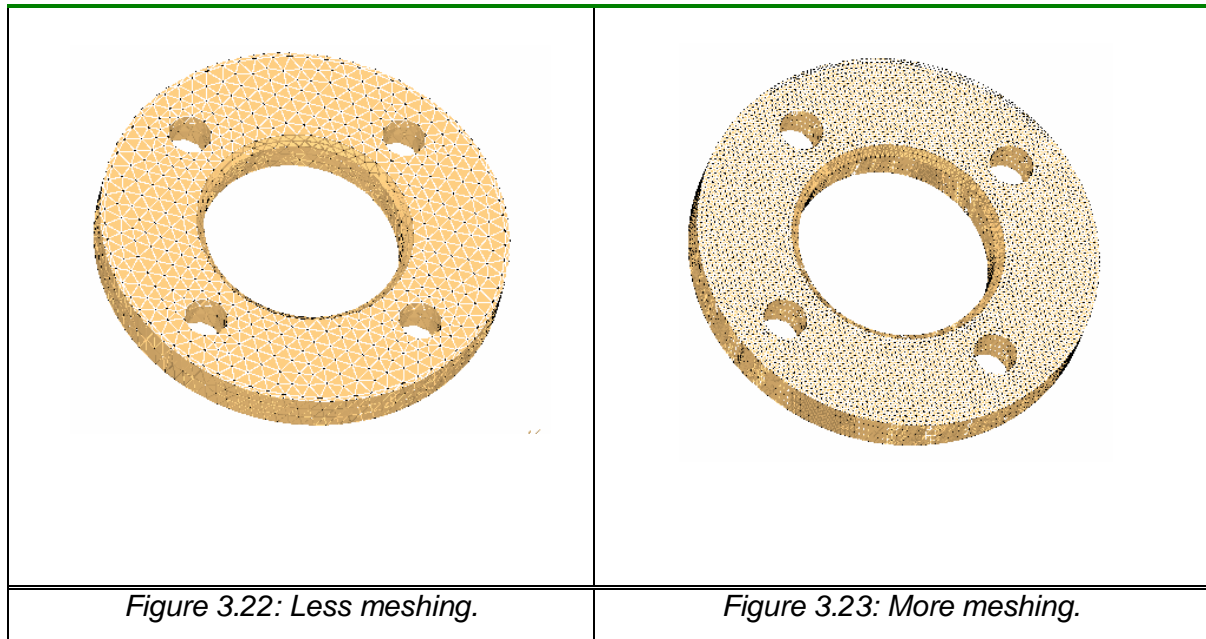
The answer to this question is that it is possible to find a good meshing using the method of *simulate and compare* between two different meshings, which consists of realizing two meshings, one with many nodes and another with few nodes, and after that observe if there exists a difference.

The following table shows this difference:

Table 3.9 : Comparing two different mesh / Injection Strategies						
Description: flange with holes / 3 bars injection						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2429	8554	10,99	4:19	1,78E-04	0,00E+00
2	17088	68237	11,42	1:20:50	1,78E-04	0,00E+00
Unit			s	h:m:s	m3	m3

It can be seen that the variation of the filling time and the volume injected between the two models is very small. But the variation of the simulation time is superior to one hour and fifteen, as the column of the simulation time shows.

In the figure 3.22 and 3.23 the difference of the quality can be seen, which can make one think that the difference is bigger, although the results of the comparison indicate the opposite.



The conclusion is that the meshing with many nodes requires a lot of calculations to find more or less the same results. Therefore the used meshing for the simulating is the model with few nodes and elements

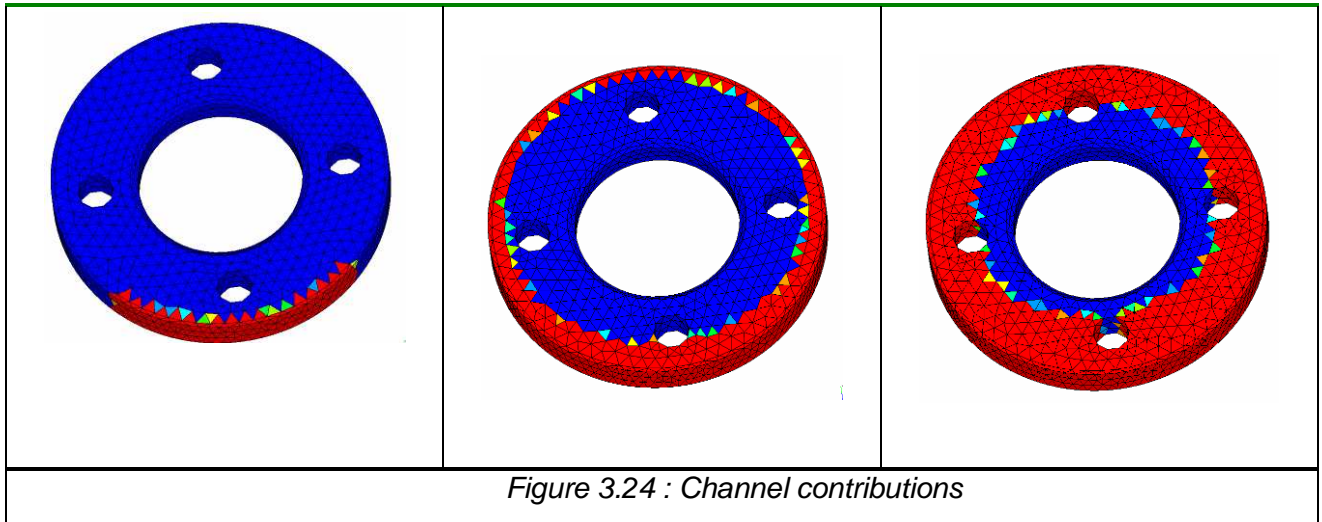
□ Channel.

After making several simulations with one injection point on the lateral face of the flange, it is possible to observe that the filling process is not homogeny and the filling time is long.

One of the possibilities that the RTM technique has is to introduce a channel to help the filling process. This channel is only a way where the fluid can flow easier. Its function is to allow the fluid to impregnate all the perimeter of the flange homogenously. For these reasons the material of the channel must have a great permeability and porosity.

In the case of the flange perimeter, this “help channel” should be a circle. But this channel cut be inner or outer. The simulations taught us that with an outer channel the filling time is reduced, a logical fact if though that it has more perimeter.

For all these reasons each simulation includes this “help channel”, which can be seen in the figure 3.24.



- Injection pressure.

The motion force in RTM process is pressure. The resin is pumped into the closed mould. The pump to use depends of the scale of manufacturing operation (200 – 400 (units / day)), the dimension of the flange and the amount of investment capital available.

The RTM process works with pressures between 1 and 10 bars. This project analyzes each strategy of injection with four pressures: 1, 1.5, 3 and 6 bars.

Observing the time of filling based on entrance pressure it will serve to choose the specifications of the injection pump. In theory when the pressure of entrance is greater, then the filling time will be smaller. But on the other hand, it will be probably that the requirements for the pump and the mould increase considerable. The cost of the pump increases and there will be a turbulent flow, a smaller quality of impregnating (more defects) and most extreme conditions inside the mould.

Another important aspect to considerate is when the RTM process works with high pressure, because the fibres are pressed away by the resin. This effect is called “wash out”. Therefore high pressure have any interest in this project.

□ *Permeability.*

From the experiments made, the following results are obtained:

Table 3.10: Permeability Experiments / Results

Permeability	
Experiment Number	m ²
1	-
2	1,05 E -10
3	1,50 E -10
4.1	5,84 E -11
4.2	6,32 E -11

In the simulations the values of permeability are as follows:

Table 3.11: Permeability's in Simulations

Description: Used permeability's in the simulations				
	K1	K2	K3	Unit
2	1,05E-10	1,05E-10	1,00E-12	m2
3	1,50E-10	1,50E-10	1,00E-12	m2
4.1	5,84E-11	5,84E-11	1,00E-12	m2
4.2	6,32E-11	6,32E-11	1,00E-12	m2
Channel (*)	1,00E-07	1,00E-07	1,00E-12	m2

(*) The justification of the permeability of the channel is described in this point.

The value of the permeability in k_3 or in the direction perpendicular to the flange (z direction) has not been evaluated in the experiments of the first block, but it has been considered to be a top value. Logically, because the resistance to the advance of the fluid is superior in the perpendicular direction to the fibres.

The permeability of the channel should be a permeable way or has a high permeability, $1 \times 10^{-2} \text{ m}^2$, because the channel is the first element to be filled with resin and allows to obtain a homogeneity filling process of the flange. The problem is that PAM - RTM calculates the transfer of resin between two different materials with different permeability correctly only when the permeability variation is of four or five orders. Therefore, in this case, the permeability must be $k = 1 \times 10^{-7} \text{ m}^2$.

In order to observe the difference of the simulations between the different values of permeability the following tables of results are realized:

Table 3.12: Simulations with permeability of experiment 2

Description: flange with holes / channel injection / 1 point injection / $k = 1,05 \text{ E} - 10 \text{ m}^2$						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2430	8554	40,16	0:05:32	1,82E-04	0,00E+00
2	"	"	25,02	0:05:46	1,82E-04	0,00E+00
3	"	"	14,12	0:05:34	1,81E-04	0,00E+00
4	"	"	5,56	0:05:38	1,82E-04	0,00E+00
Unit			s	min : s	m³	m³

- (1) Injection Pressure = 1 bar.
 (2) Injection Pressure = 1,5 bars.
 (3) Injection Pressure = 3 bars.
 (4) Injection Pressure = 6 bars.
 (Here and in the following tables)

Table 3.13: Simulations with permeability of experiment 3

Description: flange with holes / channel injection / 1 point injection / $k = 1,50 \text{ E} - 10 \text{ m}^2$						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2430	8554	42,23	0:08:24	1,82E-04	0,00E+00
2	"	"	26,31	0:08:16	1,82E-04	0,00E+00
3	"	"	11,59	0:08:05	1,82E-04	0,00E+00
4	"	"	6,11	0:07:53	1,82E-04	0,00E+00
Unit			s	min : s	m³	m³

Table 3.14: Simulations with permeability of experiment 4.1

Description: flange with holes / channel injection / 1 point injection / $k = 5,84 \text{ E} - 11 \text{ m}^2$						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2429	8554	44,27	0:06:51	1,82E-04	0,00E+00
2	"	"	28,94	0:08:02	1,82E-04	0,00E+00
3	"	"	14,12	0:07:57	1,82E-04	0,00E+00
4	"	"	7,05	0:07:53	1,82E-04	0,00E+00
Unit			s	min : s	m³	m³

Table 3.15: Simulations with permeability of experiment 4.2**Description: flange with holes / channel injection / 1 point injection** **$k = 6,32 \text{ E} - 11 \text{ m}^2$**

	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2429	8554	41,84	0:08:43	1,82E-04	0,00E+00
2	"	"	27,38	0:09:00	1,82E-04	0,00E+00
3	"	"	13,46	0:08:38	1,82E-04	0,00E+00
4	"	"	6,67	0:08:32	1,81E-04	0,00E+00
Unit			s	min : s	m³	m³

As it is can be observed the basic difference is in the time of filling. The maximum difference in the filling time between the different permeability's with the same pressure is 20 %. This difference is not important, because it is a difference of 10 seconds in the filling time of the RTM process, which can take several hours in curing, is insignificant.

Therefore in the other simulations using the value with more restrictive permeability, so the lower permeability: $6,32 \text{ E} - 11 \text{ m}^2$. With this consideration the simulations are always on the secure side.

□ Viscosity.

In the simulations a viscosity of 0.4 Pa.s, which usually is the resin viscosity epoxy's in 25 °C, is used, instead of the viscosity of the oil and resin used in the experiments, 0.06 Pa.s. The reason is that the filling process is more restrictive with a greater viscosity.

Although it is also possible to consider that a great pressure produces a increase of the resin temperature, therefore a decrease of the viscosity and filling time. But this is not likely to happen, because the used pressure is less than 6 bars.

□ *Porosity.*

When the porosity is higher the speed is higher as well thanks to the presence of more free spaces. The used porosity in the simulations is 0.60 (60 % air and 40 % fibre reinforcement).

The porosity of the channel is 1, because it represents a way where the fluid can flow without resistance and it is the first to be filled.

□ *Vent Ports.*

In the filling of the flange always there is a point where it is necessary to extract the accumulated air inside the cavity. In these points it is necessary to place a vent to be able to extract this air.

The distribution of the vent ports is realized once the filling of the flange has been observed. The placement of these depends on the geometry of the flange and on the flow front advance. For this reason there exist important differences between the simulations with holes and without holes.

Therefore there is a narrow relation between the injection ports and the vent ports. This relation can be observed in the point of *injection ports*. Also it is important to know that the vent ports complicate the mould design and manufacture.

□ *Vacuum Pressure.*

One of the possibilities to complete the injection is to use a vacuum pump in the vent ports. The majority of business firms provide pumps up to a precision of 20 mbar (absolute pressure).

The influence of vacuum pressure is the variation of the gradient of pressures, which is at the same: decreasing the filling time but no other parameter meets affect. It is like a distribution of the energy of the system, in this case “pressure”, between two sources, injection pump and vacuum pump. On the other hand, the cost increases, because it needs two pumps.

The used pressure in PAM-RTM simulations is 5000 Pa or 0,05 bars (50 mbars). When any pressure is defined in the vent ports, PAM-RTM consider absolute vacuum pressure, so 0

bars, aspect impossible to obtain. To realize a simulation with atmospheric pressure inside the mould, situation without pump, a vent of 1 bar has to be introduced.

The results without vacuum pump, with vacuum pump and with absolute vacuum can be observed in the following tables:

Table 3.16: Simulations without vacuum pressure

Description: flange without holes / injection channel / without vacuum pressure / 2 point injection.						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1 (1)	2805	10186	22,70	0:02:38	2,07E-04	2,04E-08
2 (2)	"	"	16,18	0:02:44	2,22E-04	2,29E-08
3 (3)	"	"	11,33	0:02:44	1,99E-04	2,39E-08
4 (4)	"	"	4,50	0:02:43	1,96E-04	2,61E-08
Unit			s	min : s	m³	m³

- (1) In this case the pressure of 1 bar does not make sense, because inside the mould there is atmospheric pressure. To obtain a difference of pressure of 1 bar we have to inject 2 bars.
- (2) The difference of pressure is 0,5 bar (1.5 (entrance) – 1 (vent)).
- (3) The difference of pressure is 2 bar (3 (entrance) – 1 (vent)).
- (4) The difference of pressure is 5 bar (6 (entrance) – 1 (vent)).

Table 3.17: Simulations with vacuum pressure**Description: flange without holes / injection channel / with vacuum pressure / 2 point injection.**

	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2805	10186	23,51	0:06:55	1,79E-04	1,53E-07
2	"	"	15,4	0:06:01	1,80E-04	1,56E-07
3	"	"	7,64	0:06:15	1,81E-04	1,26E-06
4	"	"	3,75	0:05:33	1,80E-04	1,39E-07
Unit			s	min : s	m³	m³

Table 3.18: Simulations with perfect vacuum pressure**Description: flange without holes / injection channel / with vacuum pressure (0 bars) / 2 point injection**

	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2805	10186	22,36	0:04:49	1,93E-04	0,00E+00
2	"	"	14,95	0:04:12	1,93E-04	0,00E+00
3	"	"	7,47	0:04:40	1,94E-04	0,00E+00
4	"	"	3,73	0:04:01	1,94E-04	0,00E+00
Unit			s	min : s	m³	m³

The maxim difference in the filling time is of 5 % between the perfect vacuum and a vacuum pump, with the same conditions of mesh and injection ports.

The difference increases when the injection with or without emptiness pump is compared. Although it is necessary to value that the differences of the filling times are not superior of 1 minute.

In this point one must value if the quality to arrange an injection pump and an vacuum pump will provide sufficient quality of the filling that compensates the investment of the vacuum pump.

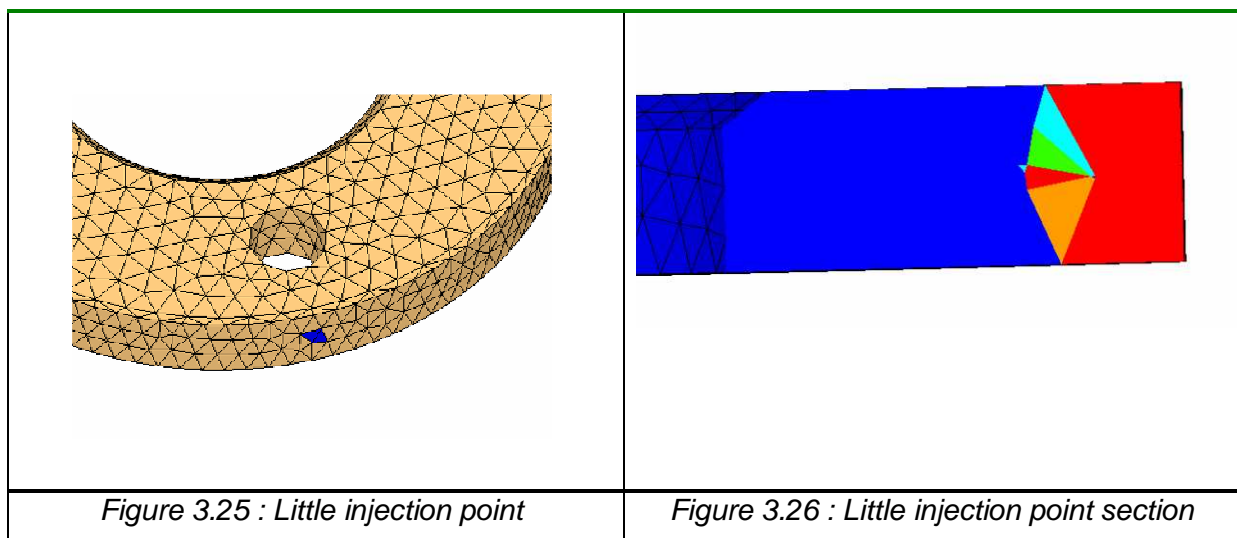
□ *Injection Ports.*

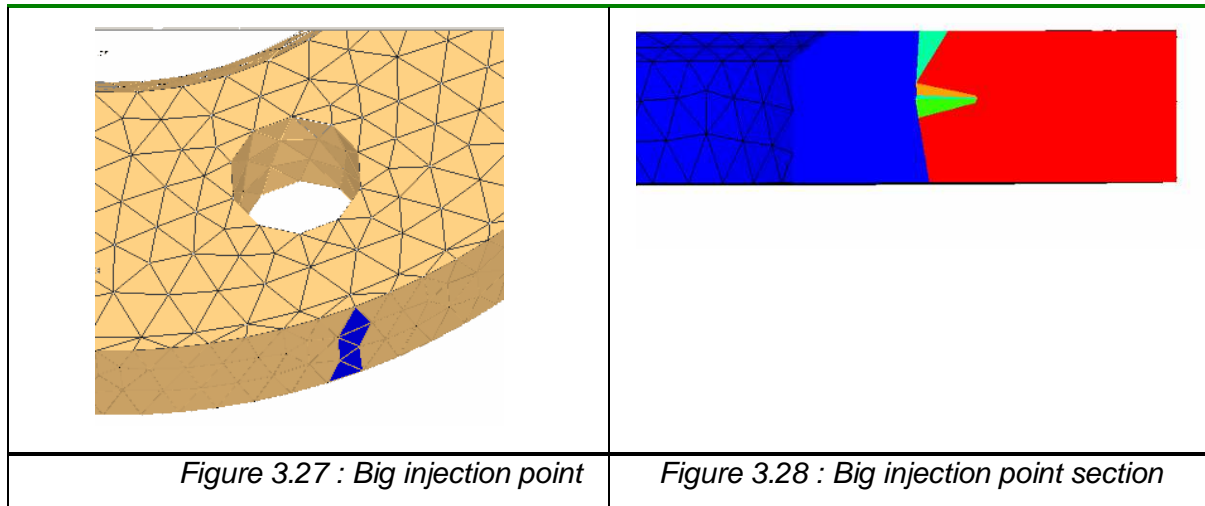
The injection port is the point where the resin is introduced into the mould cavity. PAM-RTM allows to put this injection points on the surface of the flange with the objective to see the filling process.

Therefore is obviously that there exists a lot of possibilities to inject the resin into the flange cavity.

The first simulations consist of injecting in a lateral side, superior and lower side of the flange. The comparison of filling times shows that the superior and inferior injections are slower than the lateral injection. The main reason is the lower permeability in direction z or k_3 causes a deleted flow respect the others two permeability directions. For this reason the best face to inject is the lateral face.

Another important aspect of the injection is the concrete type of the injection point. One small injection point creates a nonhomogeneous boarder or advances more rapidly inside the average, although this effect decreases with the presence of the channel. Figure 3.25 and 3.26 illustrate the advance with a small injection point and in the figure 3.27 and 3.28 with a big injection point.





Another question is what happens when the fluid is injected just lateral behind holes or lateral between holes. In the two following tables the values of the two simulations can be observed:

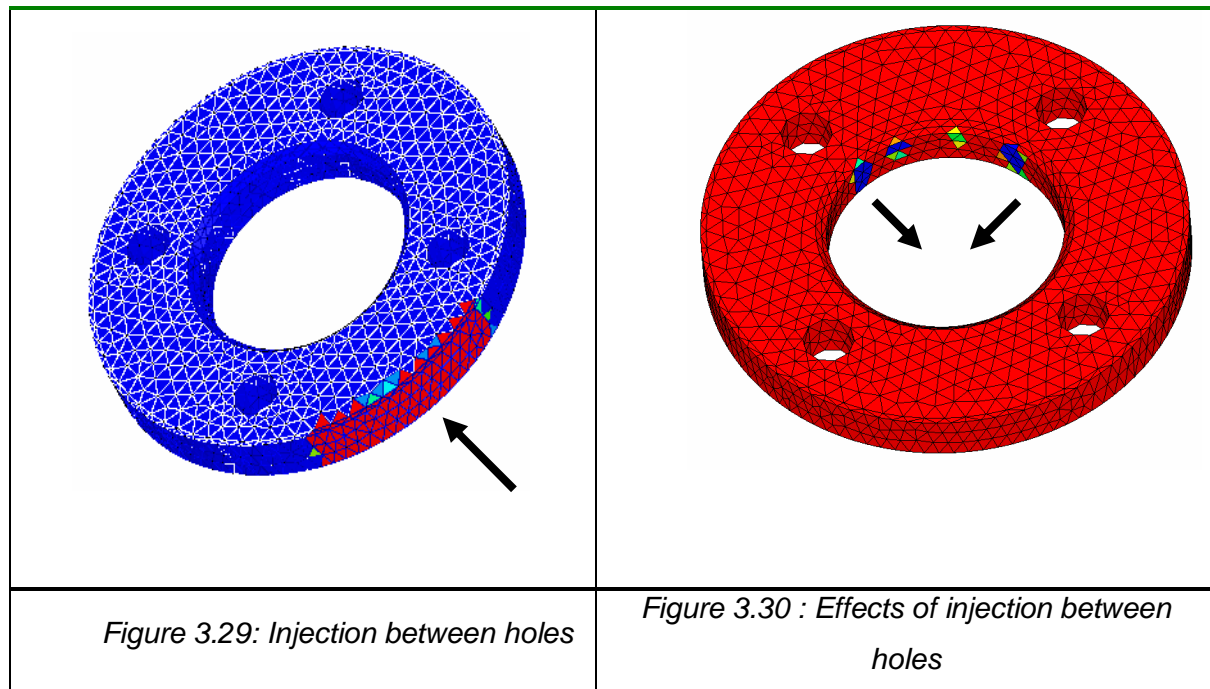
Table 3.19: Simulations injection port behind hole

Description: channel injection / behind hole / 1 point injection behind hole / 1 vent opposite						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2429	8554	34,89	5:33	1,80E-04	1,20E-08
2	"	"	22,85	6:00	1,80E-04	2,14E-08
3	"	"	11,24	6:15	1,80E-04	2,48E-08
4	"	"	5,54	5:33	1,80E-04	2,13E-08
Unit			s	min : s	m³	m³

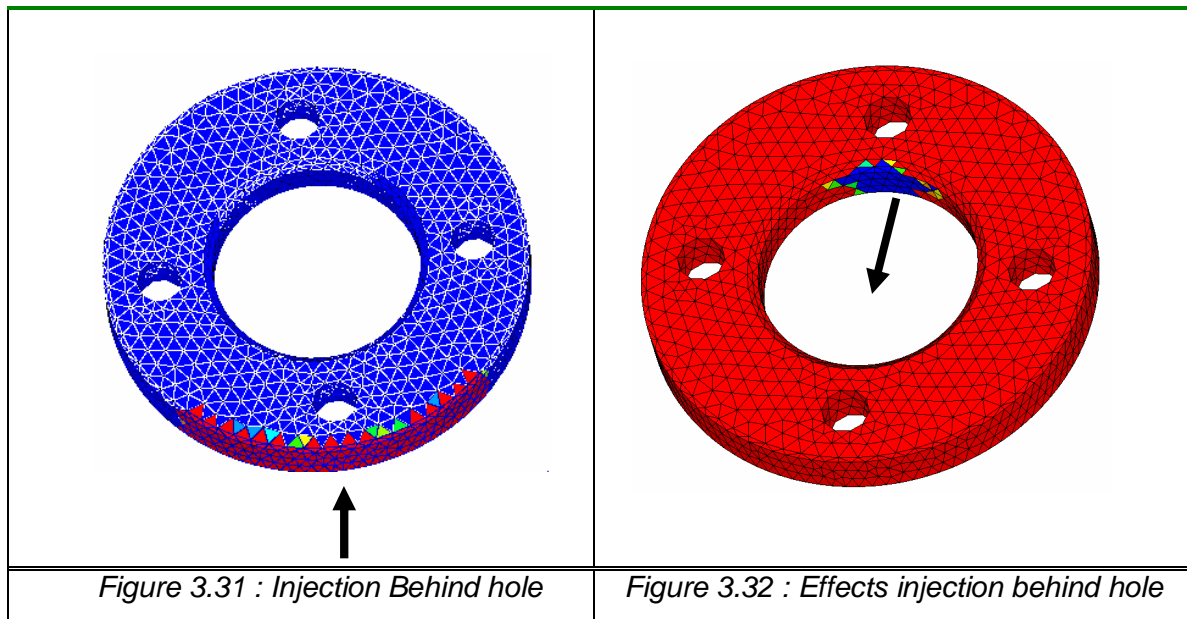
Table 3.20: Simulations injection port between holes

Description: channel injection / 1 point injection between holes / 2 vent						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2429	8554	34,607	9:52	1,80E-04	1,53E-07
2	"	"	22,66	10:26	1,80E-04	1,57E-07
3	"	"	11,10	6:47	1,81E-04	1,26E-07
4	"	"	5,50	5:51	1,80E-04	1,39E-07
Unit			s	min : s	m³	m³

It is possible to observe that differences between the filling times do not exist. The main difference can be observed with the filling process, because if the injector port is between holes two vents are necessary (figure 3.29 and 3.30), and injecting behind single hole only one is necessary (figure 3.31 and 3.32), as can be seen in the following pictures.



In figure 3.29 the injection port is between holes, and two vent port has to make between the holes an the inner cylinder, as can be seen in figure 3.30.



In figure 3.31 the injection port is behind the hole, and only one vent port has to make behind the hole on the inner cylinder, as can be seen in figure 3.32.

Another aspect to consider is to use more of an injection point. In the following tables the differences between one injection point and two injection points can be observed:

Table 3.21: Simulations with 1 injection port

Description: channel injection / 1 point injection between holes / 2 vent (50 mbar)						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2430	8554	34,607	0:09:52	1,80E-04	1,52E-07
2	"	"	22,66	0:10:26	1,80E-04	1,56E-07
3	"	"	11,10	0:06:47	1,81E-04	1,26E-07
4	"	"	5,51	0:08:39	1,80E-04	1,39E-07
Unit			S	min : s	m³	m³

Table 3.22: Simulations with 2 injections ports

Description: channel injection / 2 point injection behind holes / 4 vent (50 mbar)						
	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2430	8554	25,35	4:52	1,82E-04	6,86E-07
2	"	"	16,63	5:15	1,82E-04	7,27E-07
3	"	"	8,11	5:17	1,81E-04	6,25E-07
4	"	"	4,50	5:08	1,81E-04	7,42E-07
Unit			s	min : s	m³	m³

With two points of injection the time of filling is reduced, but not significantly. It is also necessary to have more vents ports, because the interaction of the to flow fronts cause more conflict points, therefore the design of the mould will be more complicate.

□ *Geometry.*

The geometry of the flange is in this project the factor with more influence and the critical point is the zone of the holes. In fact the strategy of injection changes with or without holes. With the intention to see this influence, the flange has been simulated with and without holes.

Table 3.23: Simulation flange with holes

Description: flange with holes / channel / 1 point injection behind hole / 0 vent (ideal vacuum)

	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2430	8554	33,18	4:53	1,79E-04	0,00E+00
2	"	"	22,34	4:31	1,79E-04	0,00E+00
3	"	"	10,99	4:19	1,78E-04	0,00E+00
4	"	"	5,49	5:00	1,79E-04	0,00E+00
Unit			s	min : s	m³	m³

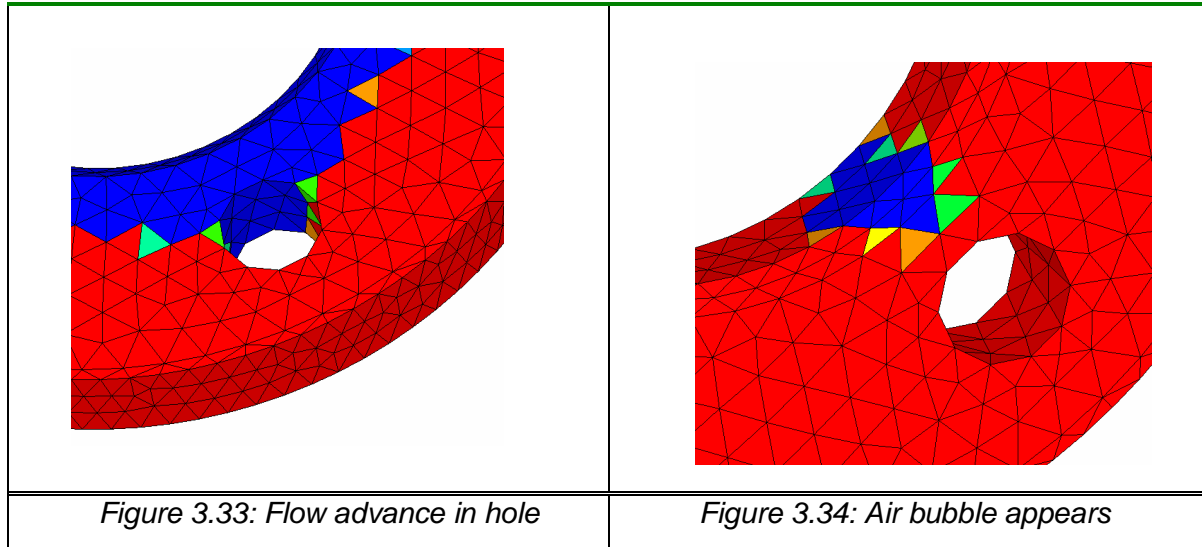
Table 3.24: Simulation flange without holes

Description: flange without holes / channel / 1 point injection / 0 vent (ideal vacuum)

	Nodes	Element	Filling Time	Simulation Time	Injected Volume	Lost Volume
1	2805	10186	32,44	0:06:19	1,93E-04	0,00E+00
2	"	"	21,73	0:05:27	1,93E-04	0,00E+00
3	"	"	10,86	0:05:13	1,93E-04	0,00E+00
4	"	"	5,43	0:05:16	1,93E-04	0,00E+00
Unit			s	min : s	m³	m³

As can be seen in table 3.23 and table 3.24, the difference between the filling time with and without holes is nonexistent.

But observing the figure 3.33 and figure 3.34, which show the flow front advance, it is easy to see that the perimeter of the hole provokes a delay in the flow front. Therefore the consequence is that an air bubble, so a defect appears in the internal part of the flange and just behind the hole.



3.3.4 Results and discussions

Table 3.25: Summary of RTM Simulations

Channel to help the fluid	Injecting directly on outer channel allows a homogeny impregnation all around the perimeter of the fibre reinforcement. It must have a high permeability and a high porosity.
Injection Pressure	A good solution is injecting between 1 and 3 bars, because is the pressure which give the greatest quality between filling time and quality, and a great pressure, for example 6 bars, give a extremely short filling time, which in reality can cause defects, although PAM RTM does not detect that.
Injection Ports	Only one injection point does not cause a blow between two flow fronts and allows an acceptable filling time. This injection port situate behind hole demands only one vent port.
Vent Ports	With the described injection port, the vent port must be situated in the interior hole in the opposite side of the injection port (See figure 3.32).
Filling Time	Any filling time is superior of 1 minute even varying the pressure from 1 bar to 6 bars, therefore using a low pressure is possible to reach a homogeny filling process and without defects.
Defects	The possible defects are concentrated around the small holes, and concretely, in the zone between the perimeter of the interior hole and the small holes, where can form air bubbles.

4 Basic Design of RTM mould

- ❑ Objectives.
- ❑ Factors with influence in RTM mould design.
- ❑ Mould materials.
- ❑ Mould cavity.
- ❑ Moulds Parts.
- ❑ Mould Manufactured.
- ❑ Mould costs.

4.1 Objectives of this basic design

The first part of this chapter consists of defining the main characteristics of the RTM mould, analyse which possibilities exist and select one of these as the solution. The results of the simulations will guide this design of the mould characteristics.

The second part of this chapter (Mould Manufactured) describes the constructed mould and the adaptations and changes realised in the designed mould, therefore in this point is possible to observe the changes realised between the design and the fabrication in order to adapt the design for manufacturing the final prototype RTM mould.

4.2 Factors with influence in RTM Mould design

The flexibility of the RTM process allows a wide range of options when considering mould design and manufacturing. Many alternative materials and construction methods can be used to manufacture and design the mould.

The following list is a list of items which should be considered when deciding upon a correct tooling route for a particular application, the relative importance of each item being dependent upon the specific application [RKM97]:

Table 4.1: Factors in RTM mould design

Relevance in the solution	Yes	No	Why?
Component and mould cost	✓		Minimise the cost of the mould is the main objective. The characteristics of the flange are imposed, therefore there is not a big range to play.
Component and mould quality	✓		The flange with the demanded characteristics and without defects depends on the mould quality.
Mould manufacturing lead time	✓		A simply, flexible and no robust mould allows the lowest manufacturing time.
Number of components to be produced		✓	The future objective, in this project is not contemplated.
Component manufacturing cycle time	✓		One of the keys of this design. It is composed for: preparation time, filling time, curing time, demoulding time and the extra works.
Dimensional tolerances and surfaces for the component		✓	The german normative indicates the tolerance of the loss flange.
Size and shape of the component	✓		The shape is the factor with greatest influence in this design.
Reproducibility requirements	✓		One hopes the same characteristics for each flange produced.

Size and shape of the mould	✓	To minimise the cost and to improve its movements.
Weight of the mould	✓	Weight has low importance, because the flange and the mould have a small size.
Mould Stiffness	✓	Necessary for the deflections in the closing pressure.
Mould strength/fatigue life	✓	One hopes temperature and pressure strength.
Mould durability	✓	One hopes doing a lot of experiments.
Operating pressure and temperatures	✓	This mould will operate between 1 and 6 bar and with a temperature above 60°C for long periods.
Proposed venting and sealing	✓	Injection and ejection strategy selected in the simulations, is one of the keys of this design.

4.2.1 Categories of RTM moulds

Tooling can be categorised as rigid, semi-rigid or expendable. Rigid tooling describes both monolithic metal tooling used in high volume manufacture and sell moulds which are stiffened locally in order to control mould deflection. The major characteristics of this approach are the ability to use the process for either vacuum or pressure infusion, dimensional tolerances can be maintained, the laminate thickness is controlled and, provided that the clamping force and tool rigidity are sufficient, very high fibre volume fraction composites can be processed. Semi rigid tooling approach requires one rigid tool and a second compliant tool face which is usually elastomeric [RKM97].

4.3 Mould materials

In the mould design different variables play a role but the material of the mould plays a central importance.

The following list is a list of items which should be considered when deciding upon a correct tooling route for a particular application, the relative importance of each item being dependent upon the specific application:

Table 4.2: Possibilities of the Mould materials

Materials Possibility	Advantages	Inconvenient
Glass / Epoxy	Low cost. Short manufacturing time. Light weight construction.	Low mould live. Low strength. Low thermal conductivity. Low corrosion resistance.
Nickel	High mould live. High Tolerance. High mould live. High strength. Low weight. High temp. resistance.	High investment. Low thermal conductivity. Long time manufacturing.
Tool steel	High pressure injection. Easy to repair. Easy to manufacture High mould life.	High investment. High weight. Long time manufacturing.
Aluminium	High thermal conductivity. Easy to repair. High strength/weight ratio.	High investment. Long manufacturing time. Low mould live.
Copper Alloys	High thermal conductivity. High strength. High resistance corrosion. High polish.	High investment.
Others	Beryllium copper alloy, Chrome copper alloy, Chromo Silicone copper alloy.	

The selected material is the steel. There exist different reasons, but the main reasons are that steel can be mechanised easily, it is easy to repair and the most important reason is that it provides a good tolerance of the loose flange, what means a good quality of the component and this is one of the main objectives of this project. Another important aspect is that steel is a material which factories and workers are familiarised with thus the manufacturing becomes more fast and effective.

A part of the described characteristics other aspects such as a high stiffness which maintain the dimensions of the loose flange during the impregnation, it is less prone to wear than the alternative mould materials and does not impose a temperature restriction on the moulding process.

The disadvantage is the high investment of the mould, but one hopes that the volume of the loose flange production becomes sufficiently elevate to amortize this cost. In fact most of the steel moulds are designed when one wants obtain a quality component or piece as the first point and then the cost as a secondary point.

The explication about the mould design development begins in the next point. The design begins with solving the geometry conditions like the central hole and the inner holes, followed by the inclusion of the injection and vent ports in the design development and concluding with defining the other parts of the mould.

4.4 Mould Cavity

It is clear that the cavity of the mould must reproduce the geometry of the loose flange, but in this case is also necessary to solve the problem of the holes and of the channel.

4.4.1 Holes Geometry

The flange has two types of holes, the central hole and the inner holes.

- **Central Hole**

This hole has a radius of 41,25 mm and contains a chamfer of 45° and a side of 3 mm, as can be observed in the appendix number A.3. The proposed solution consists of using a cylinder which reproduces the interior face of the flange as shown in figure 4.1. This cylinder is united with the upper part of the mould with screws.

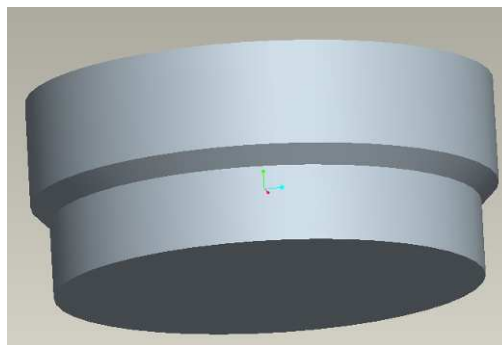
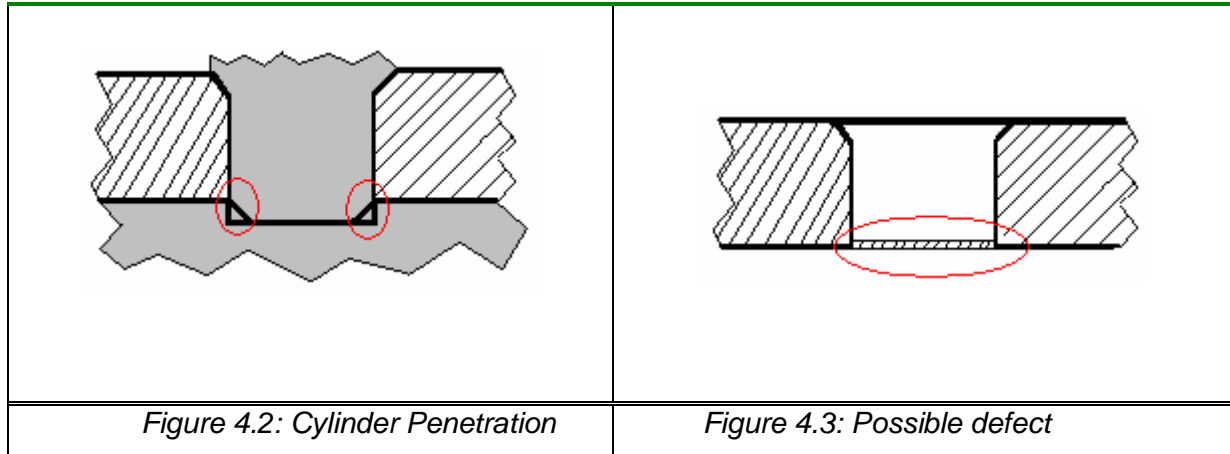


Figure 4.1: Cylinder 1

As it can be seen in the figure 4.1 the cylinder is divided into two diameters: superior and inferior. The superior diameter has contact with the upper part of the mould, so that is the part where the cylinder is screwed to the mould. The inferior part of the cylinder measures 82,50 mm which is the radius of the central hole. Between both diameters exists a slope which will creates the chamfer of the flange.

The inferior part of the cylinder has 5 mm more length to penetrate in the lower part of the mould. The objective is to eliminate a possible imperfection, because the contact between the cylinder and the lower part of the mould could be not perfect, as can be seen in figure 4.3.



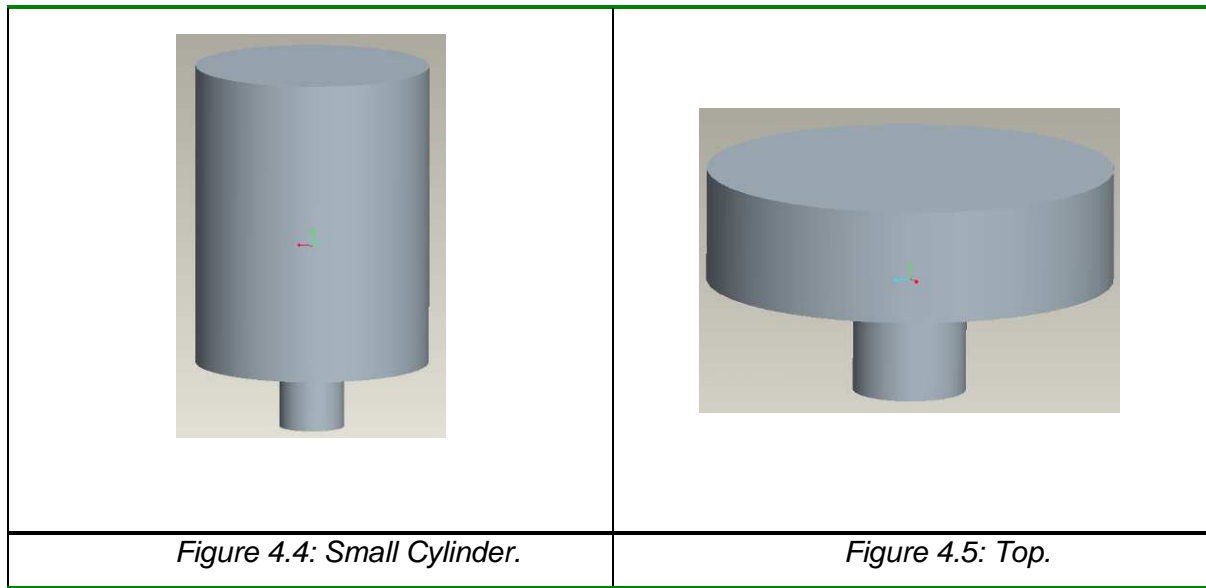
Another important aspect is that a more flexible mould is obtained using the cylinder, because the central hole of the flange can be varied only by changing the cylinder dimensions without touching the rest of the mould.

- **Inner Holes**

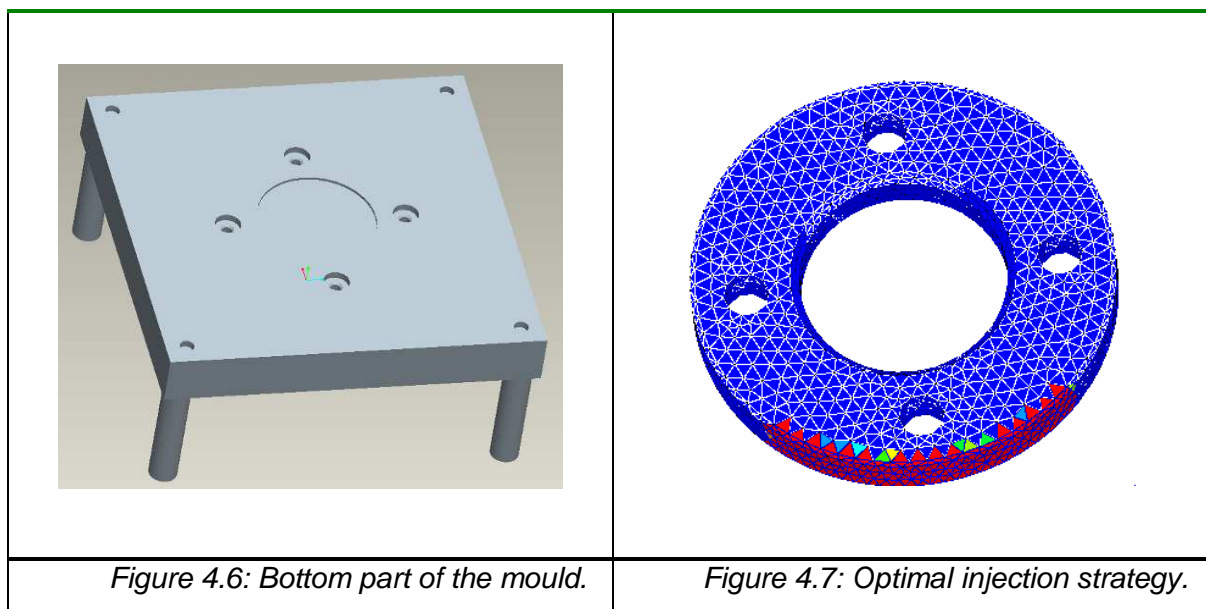
The accomplishment of the inner holes is the most conflicting point. It is clear that the injection with or without holes affects the development of the mould design and the properties of the final flange. For these reasons the proposed solution considers the possibility to have a mould able to make flanges with and without inner holes.

The solution consists of 4 small cylinders which can be screwed in the bottom part of the mould. The space create by these small cylinders generate the holes in the mould cavity. When the inner holes are not desired, then it is necessary to remove the small cylinders because the mixture can occupy this space and after that 4 tops are introduced into the screw holes in order to avoid that resin flows into the lower part of the mould.

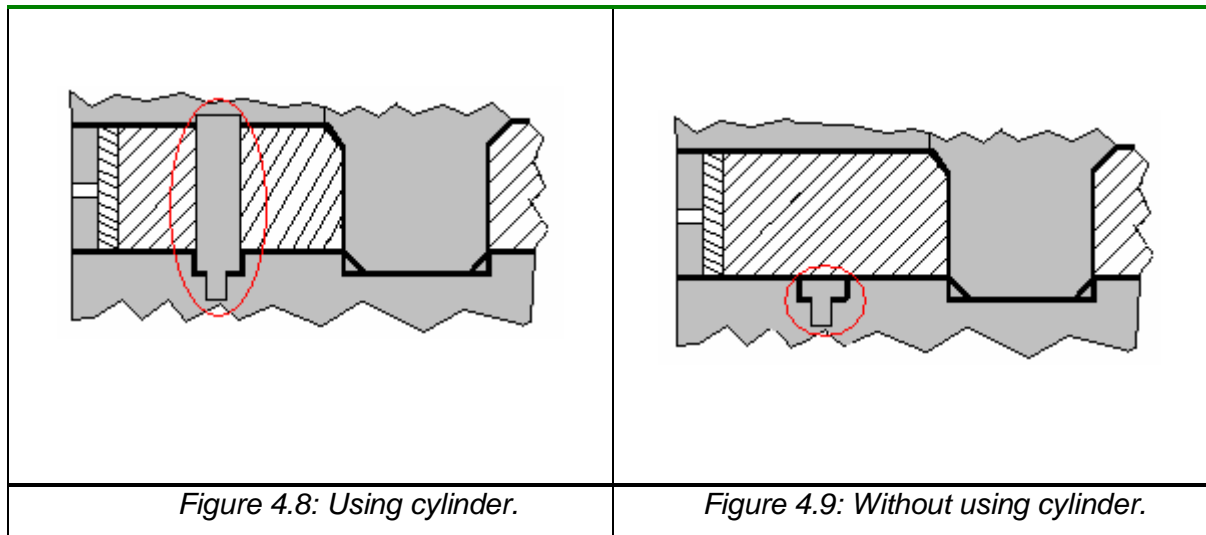
Figure 4.4 and 4.5 show the small cylinder and the top.



In figures 4.6 and 4.7 the distribution of the subsection holes, where the small cylinders can be screwed, is shown. This distribution is realised because the optimal injection strategy calculated in the RTM simulations consists of using only one injection port situated behind the hole as can be seen in figure 4.7.



In figure 4.8 and 4.9 the difference of using or not using cylinder is demonstrated. In the first figure one can easily see that when the mixture comes inside the mould cavity the occupied part of the cavity for the cylinder becomes empty of resin and fibre reinforcement and therefore the inner hole is created. In the second figure the cylinder is substituted by a top, with the mission to cover the hole where the cylinder is screwed and then here the flange will be produced without inner hole.



As it happens with the central cylinder, the diameter of the inner cylinders can be variated to obtain another type of flange.

4.5 Mould Ports

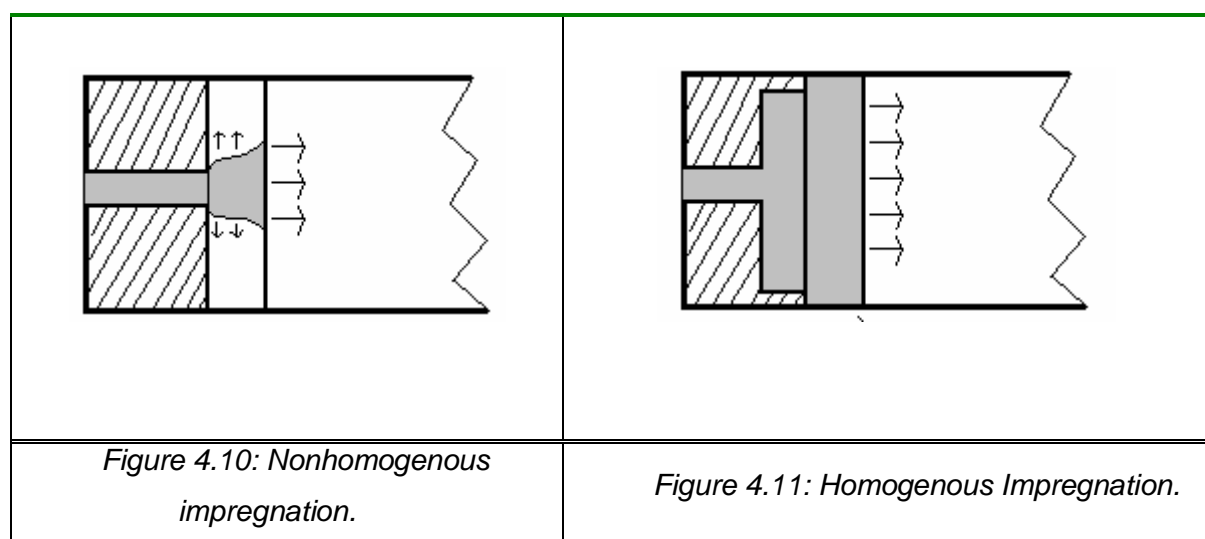
The selected strategy in the simulations phase guides how the resin has to be injected into the RTM mould. The injection port is situated behind one hole and the vent port in the opposed hole and at the inner hole. But several aspects have to be considered as follows.

4.5.1 Injection Port

First, the mixture (resin / hardener) is injected into the mould at the temperature indicated by the technical characteristics of the resin, normally greater than 20°C or more degrees, while the resin and the hardener begins to interact. The RTM process is designed to react after the injection process and before the cavity of the mould becomes completely full, but the resin which circulates through the injection ports will be completely full when the reaction cure appears. The consequence is that the mixture becomes hard and ports become saturated.

Therefore it is necessary to eliminate this hardener resin inside the injection and vent ports. The simple solution is boring the ports with a drill, but that implicates linear ports in order to drilling make possible.

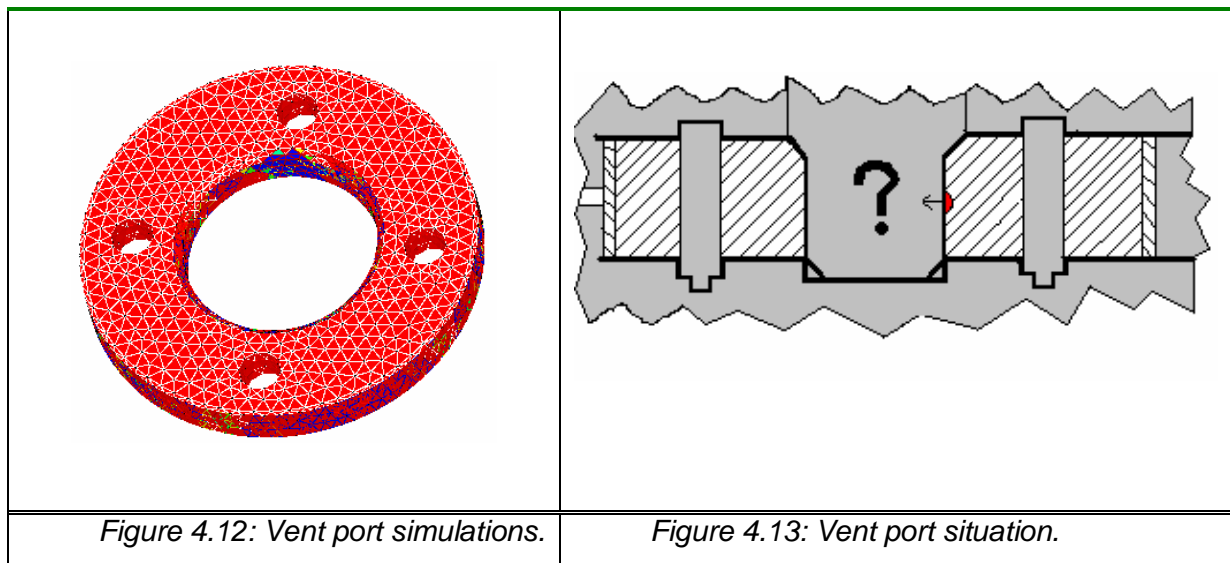
Another important subject is the connection between the injection port and the channel. As it has been explained, for a homogeneous impregnation of the flange it is necessary that the channel is injected in all its height and not only in one point of the channel, as can be seen in figure 4.10 and 4.11.



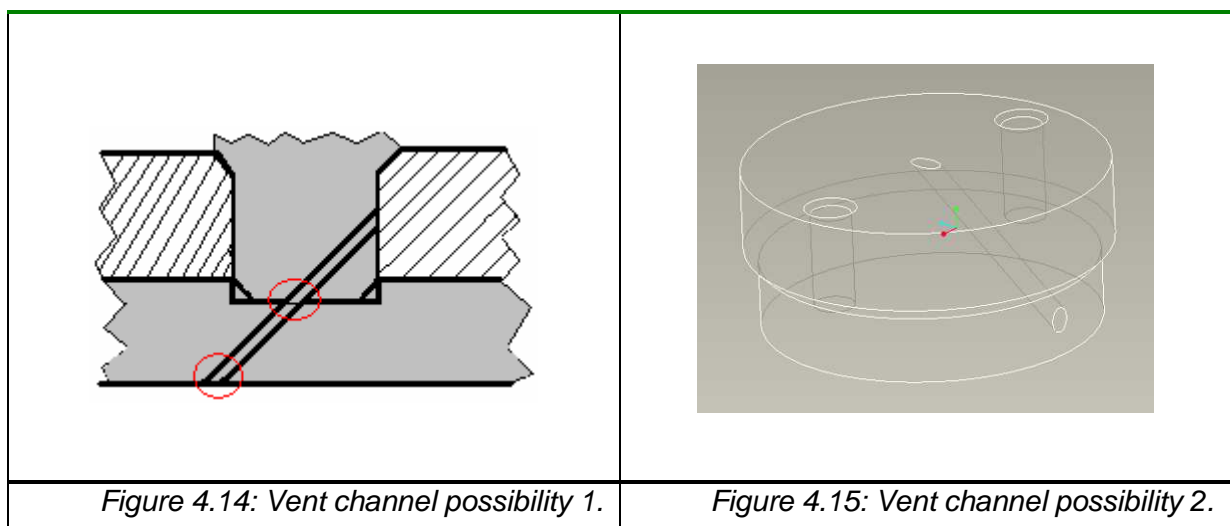
The first option will be carried out, although the second option seems better. The reason is that the possibility to increase the diameter exists always and the first option is easy to mechanise.

4.5.2 Vent Port

Another important aspect to observe is how to evacuate the air of the cavity if the situation of the vent port is known. The figure 4.12 shows the last point of the flange to be filled, so where the vent port has to be situated.



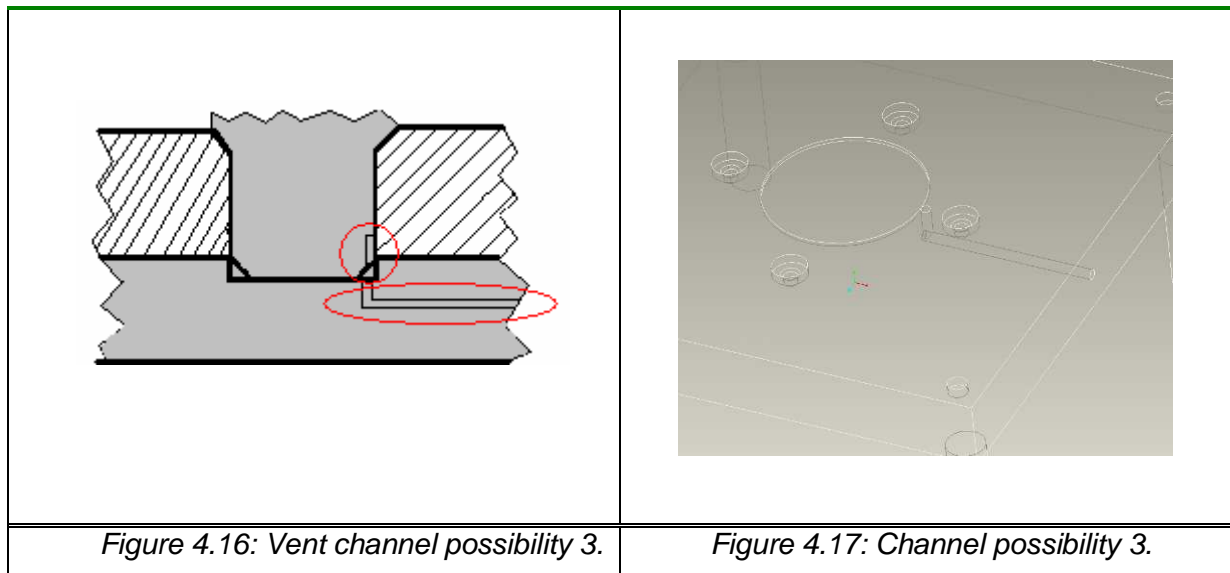
The first toughed solution consists on oblique channel of vent which allows the air extraction, figures 4.14 and 4.15 shows two possible oblique vent channel. This channel has to be a straight channel to be able to bore.



In figure 4.15 the vent channel has a negative slope, so the gravity helps with the evacuation of the mixture. But this solution creates assembly problems, because the vent channel has to cross the cylinder and the inferior part of the mould, therefore the connection of these parts of the vent channel becomes conflictive and also the degree of mechanisation becomes difficult.

In addition this venting system becomes difficult for boring because if the slope is negative it is necessary to turn the mould, as figure 4.16, and if the slope is positive the presence of the system for closing the mould could annoy the process of boring as figure 3.6.

Finally the selected solution appears in the figure 4.17.



The solution consists of using a cylinder with a chamfer in the top surfaces which penetrates into the top part of the mould and of creating a little orifice in the bottom side of the central cylinder where the vent point must be situated. Therefore the resin leaves the mould cavity through this orifice to the cavity generated by the chamfer and then circulates through the conduct of the bottom part of the mould.

A future possibility to solve the problem of boring could be a valve system. This valve system consists of two valves which can detect flow of fluid, the first valve situates in the injection port and the second situate in the vent port. The operation of the system will be simple: if the second valve detects fluid the first becomes closed, so the injection is stopped, and also the second becomes closed.

4.6 Mould Parts

The different parts of the RTM mould are described in this point. Until this point the central cylinder and the bottom part of the mould are developed and now the other parts of the mould are studied.

HASCO is an enterprise that provides a guide which has the objective to help with the construction of the mould. The guide offers multiple possibilities which allow a modular mould construction, that as its names says, consists of choosing different module or pieces and making the own assembly.

This solution offers the possibility to adapt the conditions of the central cylinder and the bottom part of the mould in the factory, because it allows the workers of the factory to have only small and simple pieces, therefore they can adapt the hoped characteristics with more facility.

4.6.1 Middle Part

It can be seen that lower part of the mould, where the small cylinders are fixed, is completely flat (figure 4.7). Therefore an intermediate part which closes the perimeter, circle, of the flange is necessary. It also has to connect the lower and the upper parts of the mould. For this reason an intermediate part is introduced as shown figure 4.18.

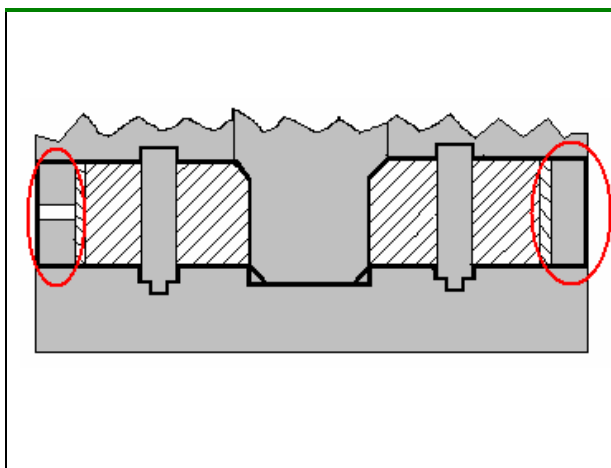


Figure 4.18: Middle Part Situation.

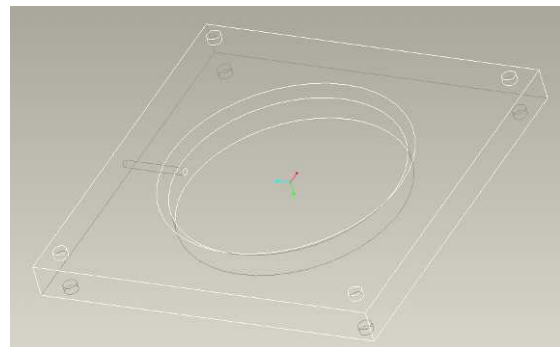
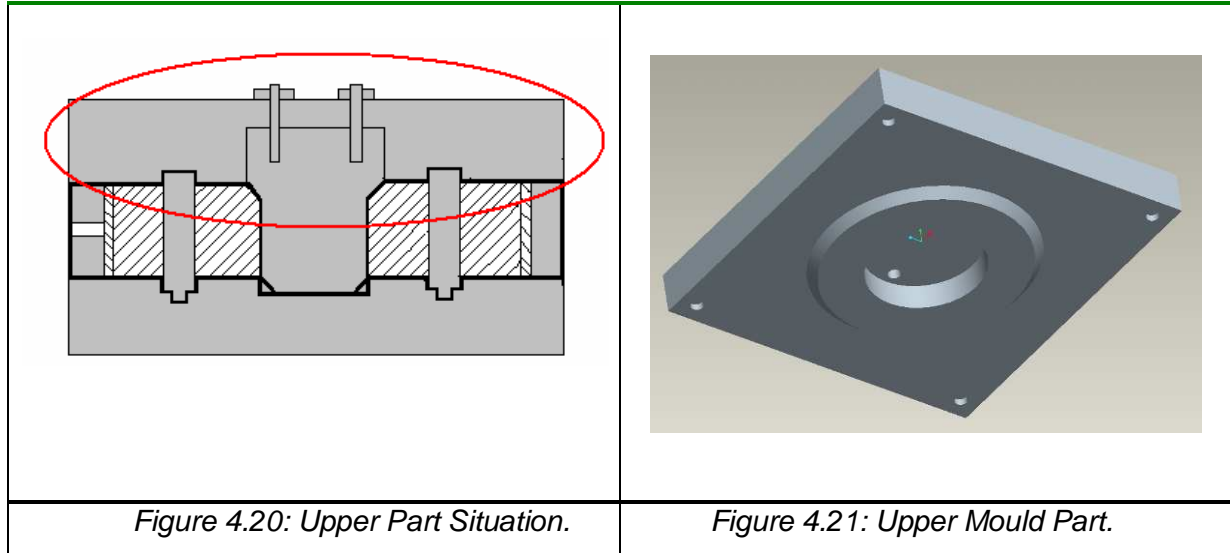


Figure 4.19: Middle Part Modul.

Additionally as it can be observed in figure 4.19 the middle part contains the injection port.

4.6.2 Upper Part

The upper part of the mould has the function to fix the central cylinder and to close the cavity.



As it can be seen in the figure 4.20 the union between the upper part and the central cylinder is realized with bolts. This is one of the reason for not using a diagonal vent port with a positive slope, because the bolts can interrupt the process of venting.

Additionally it is possible to observe how the small cylinders, which realise the inner holes of the flange, penetrate some millimetres in the over part of the mould. This penetration allows that the inner holes have any defect, therefore this concept is the same as between the central cylinder and the upper part of the mould.

The experience demonstrates that a little quantity of fibres are grouped in the upper surface of the fibre reinforcement, therefore a little space in the mould has to be realized. Figure 4.22 and 4.23 show this space situated between the middle part and the upper part.

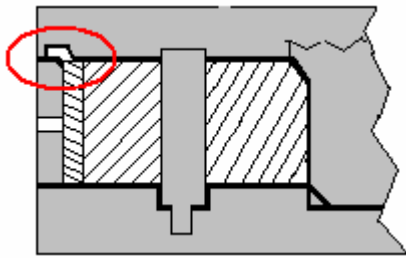


Figure 4.22: Upper Part Situation.

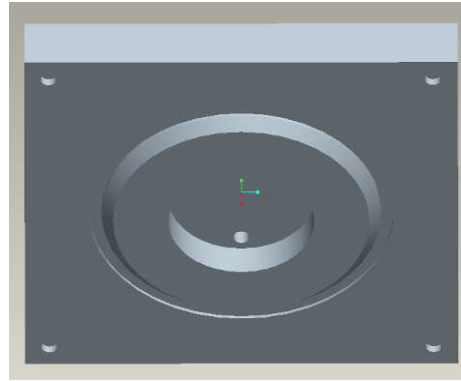


Figure 4.23: Upper Part Mechanized.

4.7 Assembly Sequence

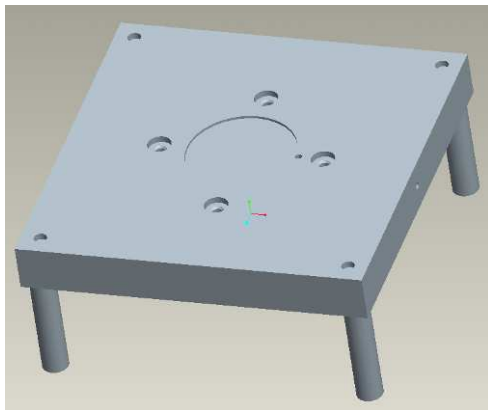


Figure 4.24: Assembly 1.

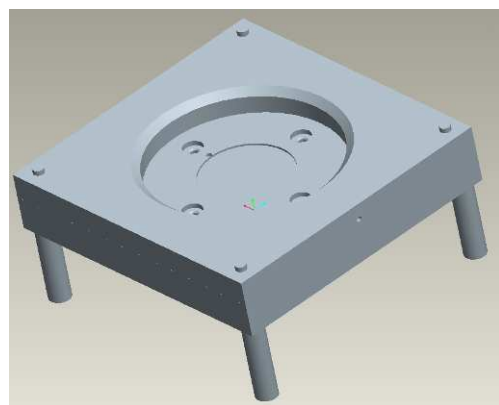
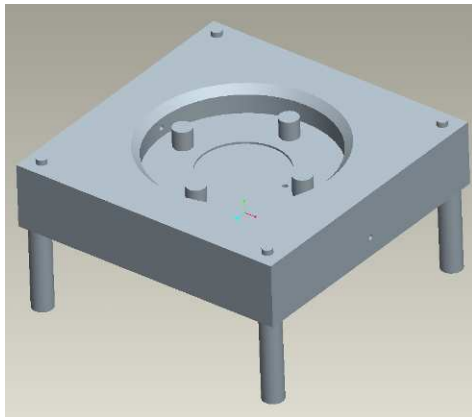
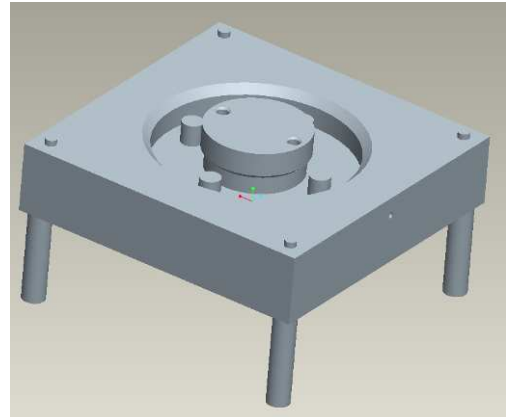
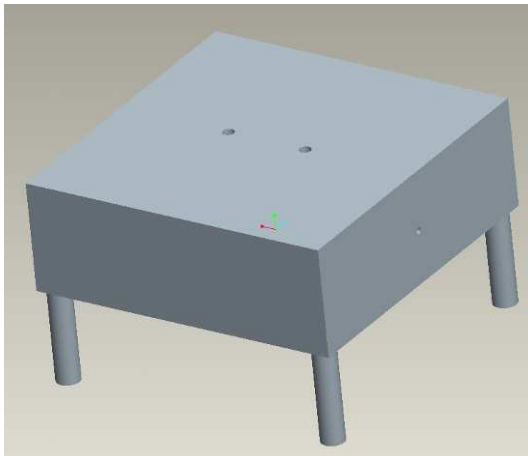
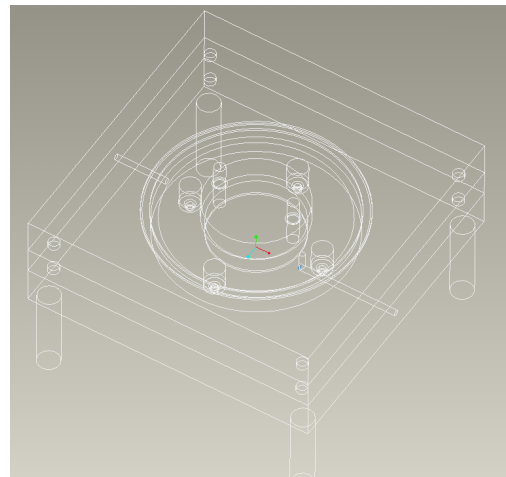


Figure 4.25: Assembly 2.

*Figure 4.26: Assembly 3.**Figure 4.27: Assembly 4.**Figure 4.28: Assembly 5.**Figure 4.29: Assembly 6.*

4.8 Mould Closing System

The closing system must be designed to transfer pressure between the different parts of the mould. This design has to consider the influence of the clamping forces, internal cavity pressures and thermal stresses. The effects of these parameters are following described.

- **Clamping forces**

Even low closing pressure can generate deflections in the mould which can affect the thickness of the flange, for this reason the mould and their supporting structure must be sufficiently stiff to resist such deflections. In fact this is one of the main reasons why steel mould has been selected, because steel provide the required mechanical stiffness.

- **Internal cavity pressure**

The fluid pressure during the impregnation in light RTM is generally a low factor because the injection pressure is not higher than 6 bars. In other techniques such as SRIM this parameter has more importance because the pressure can increase to 50 bar.

- **Thermal Stress**

The cure reaction generates a dynamic pressure inside the mould during the mould filling, although in the present case one hopes that this effect becomes low, because the resin used generates low temperatures during the reaction.

There exist a lot of systems that can be used for the mould closing as such screws, gaps, pistons, etc. But as can be seen the necessities of closing are not so high and also the mould design demands a simple solution, therefore a system using a plate compressed by different gaps distributed around them will be used. This system is the same of the permeability experiments.

Figure 4.30 shows the plate on the upper part of the mould and figure 4.31 shows the gaps.

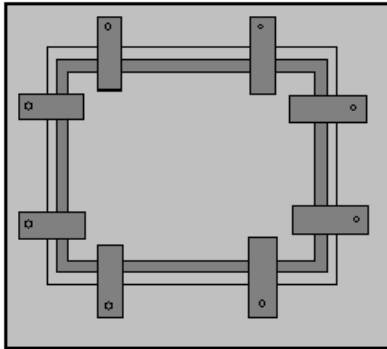


Figure 4.30: Clousing Plate.

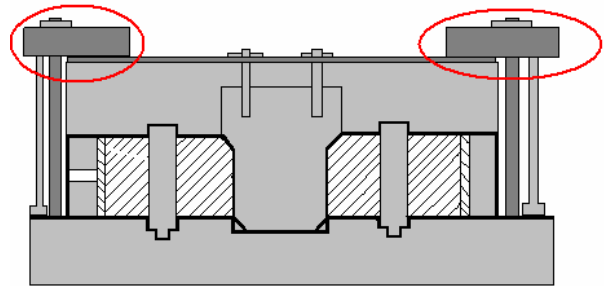


Figure 4.31: Clousing Gaps.

4.9 Mould Manufactured

Once the final solution is defined the factory starts to construct the mould. During the construction period the workers, using their experience, propose some changes in the mould design. These contributions do not change the solution of the phase of the design, but only try to distribute some elements of the mould, with the objective to make the construction and the assembly more effective and easier.

These adaptations are:

1. The central hole is united on the bottom part of the mould instead of the upper part, and the chamfer is also inverted.
2. The vent port is situated in the upper part of the mould and the central cylinder is not mechanised, only the upper part.
3. The mould includes different spaces where the mould can be opened using handles, therefore it is a system for opening the mould.
4. The inner cylinders do not penetrate in the upper mould part.
5. In order to improve the collocation and the pressure between the weave of fibre inside the mould cavity the border between the upper and middle part of the mould becomes sealing.
6. Instead of selecting a closing system with gaps, a hydraulic press is selected. The main reasons are: great closing pressure, temperature control, low preparation time, etc.

Finally the different parts of the designed mould with the explained adaptations can be seen in the following figures.

4.9.1 Bottom Part and Central Cylinder

The bottom part is a plate of 24,50 x 24,50 x 4 cm and weight 17,08 kg. It has a central hole of 9,5 cm of diameter and 0,9 cm of depth. This hole contains the two holes where the central cylinder are screwed as can be seen in figure 4.33 and 4.34. Outside of this hole and on the surface there are four holes where the small cylinders are screwed as shown in figure 4.32.



Figure 4.32: Bottom Part.

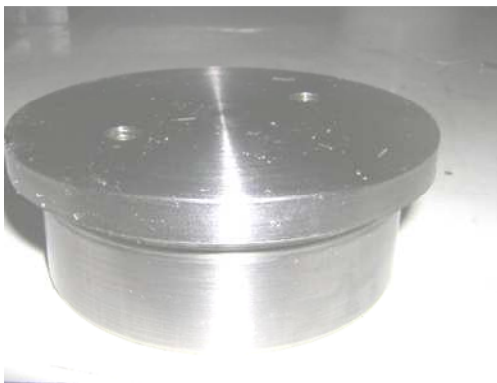


Figure 4.33: Central Cylinder.

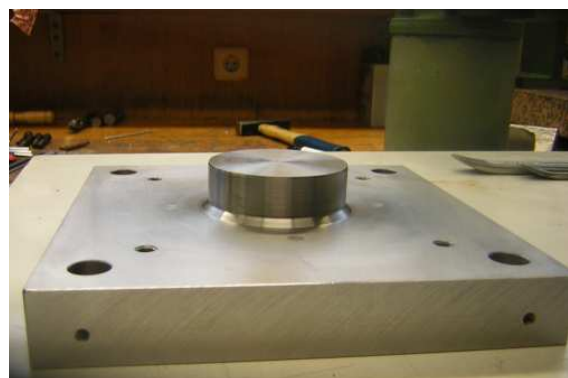


Figure 4.34: Central Cylinder Situation.

Figure 4.33 show the central cylinder. It has two different parts, the first part has a diameter of 95 mm and 10 mm length, and the second a diameter of 82,5 mm and 25 mm length, therefore the penetration of the central cylinder in the upper part is 7 mm (25 mm cylinder – 18 mm flange = 7 mm penetration). A chamfer of 45° realises the connection between these two parts of the central cylinder. This cylinder is united with the bottom part of the mould using two hexagonal screws in the bottom part of the mould.

4.9.2 Middle part

Figure 4.35 and 4.36 show the middle part of the mould. It is a plate of 24,5 x 24,5 x 2,9 cm and it contains a central hole of 165 mm of diameter. It has the injection point and the channel of injection.



Figure 4.35: Middle Part 1.



Figure 4.36: Middle Part 2.

Additionally it is possible to observe the lateral space which help the operator to disassembly the mould using handles.

4.9.3 Upper part

The upper part of the mould is shown in figure 4.37. It is a plate of 24,5 x 24,5 cm and has weight of 13,57 kg. This part has a central cylinder with a inner diameter of 82,5 mm, where the central cylinder penetrate 7 mm, and a exterior diameter of 165 mm. Between this two diameters the bottom surface of the loos flange is created.



Figure 4.37: Upper Part Modul.



Figure 4.38: Vent Port.

The figure 4.38 shows the characteristics of the vent port.

4.10 Assembly Process

The process of assembling the different parts of the mould can be seen in the following pictures. The total weight of the mould is 40,17 kg.

Two hexagonal screws unite the bottom part and the central cylinder.



Figure 4.39: Final Assembly 1.



Figure 4.40: Final Assembly 2.

Each corner of the bottom part has a little cylinder which allows to center the different parts of the mould during the assembly. In order to facilitate the assembly one corner of each part has a number which indicates the order of the assembly and the corners that has to be united.



Figure 4.41: Final Assembly3.

In addition there exist four hexagonal socket screws which unite the three parts of the mould. The disassembling has to be realised by handles in the special spaces of the corners of the mould.

4.11 Costs Analysis

Although the objective of this project is try to find a first and optimal prototype of RTM mould, it is always necessary to consider the economic viability of the RTM process, thus the cost of the mould has to be calculated, because it represents a big point in the cost of the RTM process.

Different parameters take place in the cost analysis of the RTM mould construction such as the materials, different components, workers, etc. The following table shows the approximate cost of the RTM mould construction.

- **Materials.**

The materials which compose the mould are the three blocs of steel demanded to HASCO enterprise, central cylinder, small cylinders, bolts and injectors.

The parts of the mould bought in HASCO are the bottom part, the middle part and the upper part. The total prize of these three parts is 252,95 €.

The prise of the central cylinder and the small cylinders is calculated with the actual prize of the steel and with the weight of both parts. The actual price of the steel moves around 0,5 (€/kg). The weight of the central cylinder is 1,569 kg and of one of the small cylinders is 0,0336 Kg , therefore the total weight of these parts is:

$$W_T = W_{CC} + W_{SC} = 1,569 (kg) + (0,0336 (kg)) \cdot 4 = 1,7034 kg$$

And the price:

$$C_w = 1,7034 (kg) \cdot 0,5 (€/kg) = 0,8517 €$$

The price of six hexagonal socket heat cap screws is 0,40 (€/unit) and for one injector is approximately 1 (€/unit).

- **Workers.**

One worker of the university factory wins approximately 80 €/h and the worker was working with the mould during 2 weeks (10 days), although he was only trim 40 % of the time in the mould. That represents:

$$W = 10 \text{ (days)} \cdot 0,40 \text{ (of time)} \cdot 8 \text{ (hours / day)} = 32 \text{ hours}$$

Thus the cost of the workers is:

$$C_w = 32 \text{ (hours)} \cdot 80 \text{ (€/ hour)} = 2.560 \text{ €}$$

- **Others.**

In order to consider some other costs such as the damage of the tooling, the energy consumed by the machines which have been used (press, cutter, drill, etc.), the consumption of different materials as wax or fat solvent and several others which intervene in the mould construction, an adjustment factor of 1,10 is used.

The following table show the summary of the different costs of the mould.

Table 4.3: Cost of RTM mould construction.

Subject		Cost in €	
RTM mould	Materials	HASCO	252,95
		Cylinders	0,85
		Hex. Screws	2,40
		Injectors	2,00
	Workers		2.560,00
	Total		2.818,20
	Factor of adjustment		1,10
	Total		3.100,02

5 RTM mould Proves

- ❑ Proves objectives.
- ❑ Prove Equipment.
- ❑ Fibre Reinforcement.
- ❑ Cutting Problems.
- ❑ Resin.
- ❑ Results and improvements.

5.1 Proves Objectives

The target of tests displayed in this chapter is to analyse the operation of the RTM mould. The construction of how the RTM system is constructed is extremely important to understand the possible defects in the process, although the analysis of the produced flanges is the key of a future improvement of the RTM mould.

5.2 Proves Equipment

The basic instrumentation to produce the flanges is composed for a pressure container controlled by the Dasy program (same program of the permeability experiments), a furnace where the mixture between the resin and the hardener becomes warm enough to inject the resin inside the mould cavity and to initialise the cure reaction, and finally the press which makes the sufficient pressure to close the mould correctly.

The pressure controller is in charge to provide the necessary pressure to the container of the mixture. The operator indicates which pressure is necessary in the Dasy program which sends the order to the pressure controller using a termination system SAE-BOX for the analog inputs and output signals. The pressure controller is DRPE-14-16 by Landefeld and works within a range of RTM pressure between 0 and 6 bars. The termination system is a SAE16 by Bedo Elektronik GmbH. The technical characteristics can be seen in appendix.

The injection system is the same which is used in the permeability experiments. The only difference is that the container of pressure is situated inside the furnace as show the figure 5.1.



Figure 5.1: Furnace.



Figure 5.2: Equipment.

The hydraulic press provides the closing pressure of the mould and also the temperature of the mould. Therefore, only these two parameters must be controlled by the operator. In order to refrigerate the press a refrigeration system is necessary, so both a compressor and an evaporator take part in this system.

The instrumentation of cutting the glass fibre weave consists of a rolled knife, a carton with the geometry of the loose flange, a hammer and a striker pin with round geometry to make the inner holes.


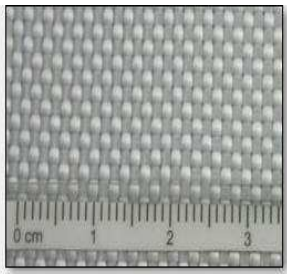
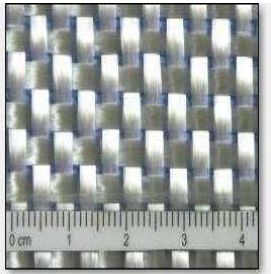
In order to make the mixture between resin and hardener it is necessary a scale to control the quantities of resin and hardener, a syringe to mix the resin and a plastic recipient where the mixture is removed using a wood spatula.

To demould the loose flange two handles and a little pneumatic press are used.

5.3 Fibre Reinforcement

In this prove different glass fibre weave are used in order to determinate which type of weave provides the greatest characteristics to be produced. Nevertheless, it is necessary to determinate if the weave used provides the proper mechanical characteristics. The first selected glass fibre weaves have been selected to be able to respond to wished objective.

In this chapter three glass weaves are testing as can be seen in Figure 5.3, 5.4 and 5.5.

		
<p><i>Figure 5.3: Weave A</i></p>	<p><i>Figure 5.4: Weave B</i></p>	<p><i>Figure 5.5: Weave C</i></p>

The used pattern is the plain weave, in which weft (filling) yarns pass alternately under and over each warp yarn. Plain weaves have the greatest level of stability which results in good handling properties. The dimensions of these weaves can be seen in appendix number A.1.

Table 5.1 Proves of the RTM mould

Weave	Company	Model	Weight (g/m ²)	Thickness (mm)
A	Lange Ritter	Interglass 92112	200	0,20
B	HP-Textile	HP-P390E	390	0,34
C	HP-Textile	HP-P600E	600	0,66

The numbers of layers to place inside the mould cavity depend on the fraction of the fibreglass volume required. This fraction normally moves between 40% and 50% of fibreglass volume.

The following example shows how to calculate the number of layers to introduce inside the mould using a determinate weave and fibreglass volume to manufacture the loss flange.

Example:

Let suppose that it wants to use a loss flange with 40% of FVG using the weave C.

- *How many weaves should be introduce inside the mould cavity?*

Possibility 1

1. The weight of fibreglass for each loss flange.

$$\rho = \frac{m}{V} \Rightarrow m = \rho \cdot V = 2,5 (g / cm^3) \cdot 108,13 (cm^3) = 270,34 (g \text{ fiber} / flange)$$

Where:

$$V = VF \cdot GFV = 270,204(\text{cm}^3 / \text{flange}) \cdot 0,4 = 108,13(\text{cm}^3 / \text{flange})$$

- GFV: *fibreglass volume (%)*.
- VF: *volume of flange (cm³)*.

$$V = \text{area} \cdot \text{height} = 150,11359(\text{cm}^2 / \text{layer}) \cdot 1,8(\text{cm}) = 270,204(\text{cm}^3 / \text{flange})$$

2. The area of fibreglass for each loss flange.

$$\begin{aligned} A &= a1 - a2 - 4 \cdot a3 = \pi \cdot (r1)^2 - \pi \cdot (r2)^2 - (\pi \cdot (r3)^2) \cdot 4 = \\ &= \pi \cdot (82,50)^2 - \pi \cdot (41,25)^2 - (\pi \cdot (9)^2) \cdot 4 = 15.011,359 \text{ mm}^2 = 0,015011359(\text{m}^2 / \text{layer}) \end{aligned}$$

Where:

- a1: *area of the flange without center and inner holes* ; a2: *area of center hole* ; a3: *area of the inner holes (see figure 2.2)*.

- r1: *radius of the flange* ; r2: *radius of center holes* ; r3: *radius of the inner holes*.

3. With this weave which .

$$P = W_{WC} \cdot A_{flange} = 600(\text{g} / \text{m}^2 \text{ of weave } A) \cdot 0,015011359(\text{m}^2 / \text{layer}) = 9,006815 \approx 9(\text{g} / \text{layer})$$

4. Therefore the number of layers or N is as follows:

$$N = \frac{270,34(\text{g fiber} / \text{flange})}{9(\text{g fiber} / \text{flange})} = 30,037 \approx 30 \text{ layers}$$

Possibility 2

Another possibility to calculate the number of layers is as follows:

$$FVG = \frac{N \cdot W_{weave}}{t \cdot \rho_{glassfibre}} \Rightarrow N = \frac{FVG \cdot t \cdot \rho_{glassfibre}}{W_{weave}} = \frac{0,4 \cdot 0,018(\text{m}) \cdot 2.500(\text{kg} / \text{m}^3)}{0,6(\text{kg} / \text{m}^2)} = 30 \text{ layers}$$

Therefore it is necessary to use 30 layers and each weave has a thickness of 0,6 mm, thus all together have 18 mm of thickness, just the thickness of the loss flange.

Table 5.2: Used weaves in the proves

Weave	Weight (g/m ²)	Thickness (mm)	Layers with holes	Layers without holes	Total thickness (mm)
A	200	0,20	90	90	18,00
B	390	0,24	47	46	11,28
C	600	0,44	30	30	13,20

The table 5.2 shows the number of layers to place inside the mould cavity when the loose flange, with or without holes, will be produced. The process of calculation is the same of the described example and only the volume and the area without holes changes.

The columns of number of layers show that no differences exist between the flange with and without holes. The reason is that holes don't make a big influence in the volume (270,34 m² with ; 288,66 m² without) and the area (0,015 m² with ; 0,016 m² without), so the need of fibre does not change.

5.4 Cutting problems

When cutting manually, the main problem is the difficulty to cut circular geometries, because the precision of the cut is reduced. In fact cutting glass fibre requires more attention than carbon fibre or hybrid.

Therefore, the ideal solution is to use something able to make precise cuttings such as precise tools. Other solutions like the laser machines are difficult to use because the glass fibre is a ceramic material, with SiO_2 , which has a high fusion temperature and also this technique requires a big investment.

The instrumentation that is used to cut the geometry is a wheel knife and a flange prototype of carton, as can be seen in figure 5.6 and 5.7. This instrumentation is inadequate to obtain a good tolerance of cut, but it is the instrumentation that arranges the factory.



Figure 5.6: Wheel Knife

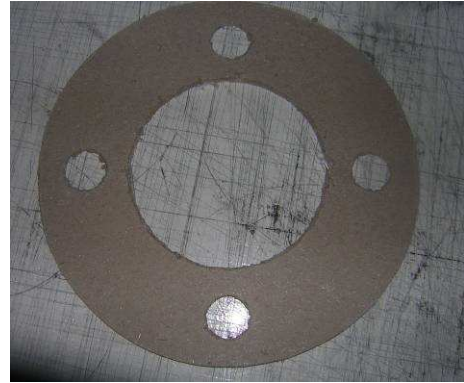


Figure 5.7: Prototype Carton

In order to have an idea of the inefficiency of the cutting process is possible to observe the table 5.3 where are displayed the time of cutting each one of the weave.

Table 5.3: Cutting times			
Description: flange without holes			
Weave	N / flange	T / layer	Ttotal
A	90	1 : 30	135
B	47	4 : 00	188
C	30	6 : 00	180
		min : s	min

There exist a big difference between cutting the weave B or C and A. The main reason is that cutting the weave B or C to obtain a circle produces some damage in the perimeter of the flange, so it is necessary to cut accurate and that implies greater time. The figure 5.8 and 5.9

shows the difference to cut accurate or in high quantity. In the other hand cutting the weave A represents less time, because it has less damages, as show figure 5.10.

<i>Figure 5.8: Damage Weave B</i>	<i>Figure 5.9: Accurate cut</i>	<i>Figure 5.10: Weave A</i>

The process of cutting the inner holes has several aspects to consider. The first aspect is how to do the cutting. The struck of the fibre with a striker pin and a hammer to obtain the inner holes can be seen in figure 5.11.

The second aspect is which type of glass fibre should be cut, because the distance between the inner and the outer perimeter is only 41,25 mm. Therefore the weave has to have a good distribution of the threads of fibre, because a breakage does not occur, as can be observed in figure 5.12 with the weave C. The reason is that there exist a few heavy threads exist (weave C) instead of many thinner threads (weave A). Therefore, an overture in the fibre geometry becomes, so the distribution of the fibre has importance in the process of cutting.

<i>Figure 5.11: Inner holes instrumentation.</i>	<i>Figure 5.12: Damage of weave.</i>

The consequence is that a defect occurs in the zone behind and ahead of the inner hole. The required time to make the inner holes of one loose flange using the weave A is greater than 1 hour and 30 minutes which is totally inefficient.

Another aspect to consider is the accumulation of fibres in the walls of the inner cylinders and the central cylinder. There is this accumulation when the layers of glass fibre cut in the same dimensions of the loose flange, then when they are placed in the mould cavity, the fibre in contact the wall and it is raised (Figure 5.13). The reason is that the holes of the glass fibre weave are cut in the exact wished diameter instead of a little bigger diameter in order to avoid this accumulation.



Figure 5.13: Accumulation effect.

5.5 Resin

The epoxy resin EPIKOTE[™] Resin 827 and amine hardener EPIKURE[™] Curing Agent 943 will be used in the RTM mould proves. Although this resin is not specially applied in the RTM process, it provides a low viscosity epoxy resin (1 Pa.s, no ideal for RTM process), good pigment wetting and a high level of mechanical and chemical resistance properties in the cured state, one hopes that can be used. The technical information can be observed in the appendix number A.2.

The mixing ratio must be 100 parts by weight of resin and 24 parts by weight of hardener. Adding more or less Hardener will not effect a faster or slower reaction but an incomplete curing could occur. Therefore if one want a slower or faster curing additives have to be introduced in the mixing.

The quantity of mixing used in each proves is calculated as follows:

1. Volume of the loose flange without holes.

$$V_F = A \cdot t = (\pi \cdot (r_1^2 - r_2^2)) \cdot t = (\pi \cdot (82,5^2 - 41,25^2)) \cdot 18 = 288.663,28 \text{ mm}^3 = 288,663 \left(\frac{\text{cm}^3}{\text{flange}} \right)$$

2. Resin volume fraction of 60%.

$$V_R = V_F \cdot 0,60 = 288,663 \text{ cm}^3 \cdot 0,6 = 173,198 \left(\frac{\text{cm}^3 \text{ mixing}}{\text{flange}} \right)$$

3. Injection tube volume.

In order to maintain the continuity of the mixing in the injection process the volume of the injection tube has to be considered.

$$V_T = l \cdot A = l \cdot (\pi \cdot r^2) = 150 \cdot (\pi \cdot 0,45^2) = 95,42 \left(\frac{\text{cm}^3}{\text{tube}} \right)$$

4. Total volume injection.

$$V_T = V_R + V_T = 173,198 + 95,42 = 268,618 \left(\frac{\text{cm}^3 \text{ mixing}}{\text{flange}} \right)$$

5. Total volume resin and hardener.

The proportions of resin and hardener in the mixing are imposed by the technical information of the resin. The proportions are calculated with the weight of the mixing. The technical catalogue of the rein not provides the density of the mixing, only the density of the resin (1.17 g/cm³) and the hardener (0.92 g/cm³) separately at 20°C, therefore the greatest density is used to calculate the necessary weight of the mixing.

$$W_M = \rho \cdot V = 1.17 \left(\frac{\text{g}}{\text{cm}^3} \right) \cdot 268,618 \left(\frac{\text{cm}^3 \text{ mixing}}{\text{flange}} \right) = 314,283 \left(\frac{\text{g}}{\text{prove}} \right)$$

But a weight of 500 (g / prove) is considered, because not succeed that resin becomes consumed during the filling process.

Therefore the quantity of hardener in 500 g. of resin has to be as follows:

$$W_H = W_T \cdot \left(\frac{24}{100} \right) = 500 \cdot \left(\frac{24}{100} \right) = 120 \left(\frac{g \text{ of hardener}}{\text{prove}} \right)$$

The mixture is made using a little recipient where there is 500 grams of resin and 120 grams of hardener and then the mixture is mixed using a wood spatula. This process is done with the presence of air which is included in the mixture as a little air bubbles. The consequence of this defect can be observed later, but in order to minimise the presence of these little air bubbles there exists others solutions as mixing in emptiness using a vacuum.

The technical information of the resin indicates that the processing temperature must be in the range between 20°C and 30°C. Higher processing temperature will shorten the life pot, for example a rise of 10°C reduces the life pot by a proximately 50%. The viscosity of the mixture at 25°C is 1000 mPa.s according of the data sheet (appendix A.2). With this viscosity it is hoped that the filling time becomes greater than in the simulations process, because the viscosity used was of 400 mPa.s at 25°C. This aspect will be observed in the results.

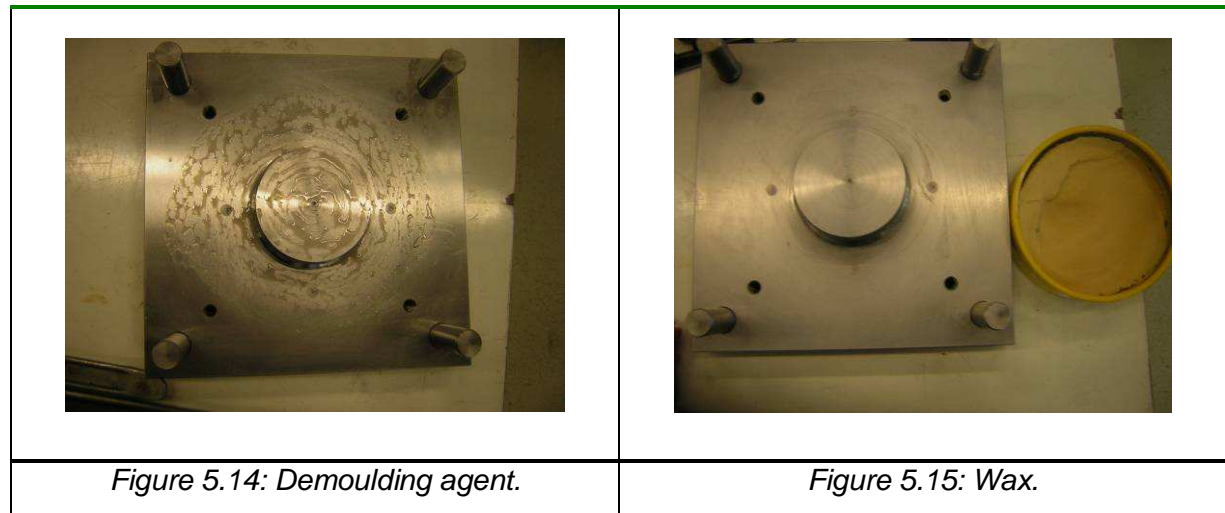
The mixture is heated up until 25°C, which is a temperature that allows the injection. In fact, as the mixture is inside the recipient of steel, which protects against the heat. It is necessary to increase the temperature of the furnace until 50°C during 20 minutes to obtain 25°C in the mixture.

The curing cycle depends on the applied temperature and the technical information of the mixing indicates 3 hours at 30 - 40°C and then between 8 – 10 hours at 60 °C for a shorting curing.

5.6 Flange Demoulding

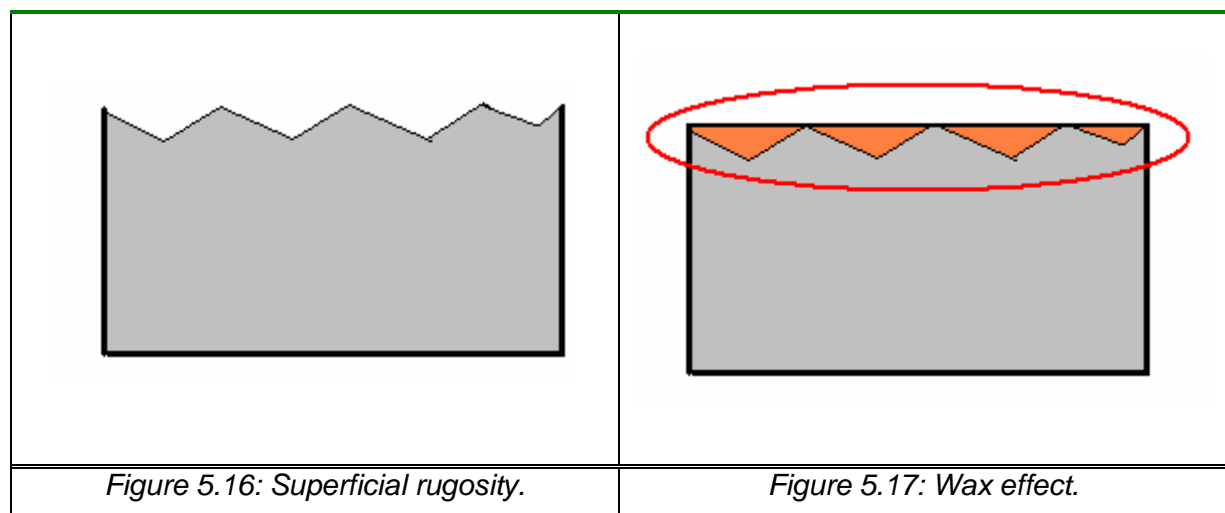
In order to be able to demould the loose flange it is necessary to have impregnated the surfaces of contact between the loose flange and the mould with a demoulding agent. However, in the first tests the impregnation instead of using a demoulding agent, a wax is used, because the demoulding agent causes a irregular layer on the surfaces of the mould

which can generate defects on the surface of the loose flange. The difference of using a demoulding agent and wax can be seen in the figure 5.14 and 5.15.



Although in the figure 5.14 the bottom part has to be dried, the surfaces become irregular because the impregnation generate little pools of demoulding agent. The figure 5.15 shows the bottom part of the mould where four layers of wax have been applied.

In fact, wax also eliminates the superficial rugosity of the mould and then it improves the contact between surfaces when more layers are impregnated. As can be seen in figure 5.16 and 5.17 wax introduced in the cavities allows a more planar surface.



The main consequence is that there is a great contact between the surfaces and then the resin has no way to come out of the mould cavity.

In order to demould the loose flange two handles are introduced in the lateral spaces to take in out. The flange is demoulded from the central cylinder using a little pneumatic press

The demoulding of the loose flange becomes easier the more loose flanges are produced and this effect can be denominated like a “mould adaptation” or “mould accommodation”.

5.7 Cost of the proves

One of the main aspects to know is the cost of producing the loose flange and with this intention the following table is created. This table shows the cost of the main tangible parameters such as resin, hardener, fibre glass and tubes, and it also tried to consider the cost of the intangible parameters such as the damage of the press, refrigerator, the consumption of electrical energy and the damage of the mould.

The table reflects the cost of the production of the loose flange with holes using the three types of weave and considers a factor of 10% within the total because exists indirect consumptions (energy, wax, etc.) and damage of the machinery (press and furnace).

Table 5.4: Cost of RTM proves.

Subject		Cost	Quantity		Total Cost	
Mixture	Resin (Epikote 827) + Hardener (Epikure 943)	17,24 (€/kg)	0,620 (gr. / flange)		10,69	
Tube		0,80 (€/m)	3 (m / prove)		2,4	
Subject		Cost	Quantity		Total Cost	
Glass Fibre	Weave A (Lange Ritter)	2,77 (€/m)	90 (units)	5 (units / layer)	0,20 (m/ lay)	3,60 €
	Weave B (HP-P390E)	1,98 (€/m)	46 (units)			3,64 €
	Weave C (HP-P600E)	2,45 (€/m)	30 (units)			1,08 €
Weave A		Weave B		Weave C		
Cost		16,69 €	16,73 €		14,17 €	
Factor adjustament		1,10%				
Total cost		18,34 €	18,40 €		15,59 €	

5.8 Results and improvements

The results of the tests with the injection conditions, the main visible defects and the photos of the loose flanges produced are showed in appendix 4. In order to analyze the behaviour of the mould flange, flanges with and without inner holes are tested.

5.8.1 Correct aspects

The following points describe the good characteristics obtained in the firsts proves.

Table 5.5: Correct aspects of RTM proves.

Filling time	Proves Equipment	Injection Strategy	Geometry
The injection pressure must be between 0,5 bars relative to allow a good impregnation. This reaches a filling time lower than 5 minutes, which does not differ from the simulation times so much (around 1 minute).	Although the equipment is not the best the obtained loose flange have a sufficient good quality and good impregnation.	The situation of the injection and vent ports reach the wished objective: total impregnation and without air bubbles around and behind the inner holes. The channel realise its function correctly.	The central and the inner cylinders allow to obtain a good dimensional tolerance and a excellent surface quality, so without errors. The dimensions are correct.



Figure 5.18: Flange with holes.



Figure 5.19: Flange without holes.

5.8.2 Proves defects

From the firsts loose flange tested to the last one, some defects are detected and they will be described as following. Some of these defects are solved during these tests, for only possible solutions are proposed .

5.8.2.1 Glass fibre not impregnated

In the first test a loose flange without inner holes is produced. The weave number A (90 layers without holes), an injection pressure of 1,5 bars and channel without fibre are used. The flange produced shows as the lateral surface is not correct impregnated, as can be seen in figure 5.20 and 5.21.



Figure 5.20: First flange produced.

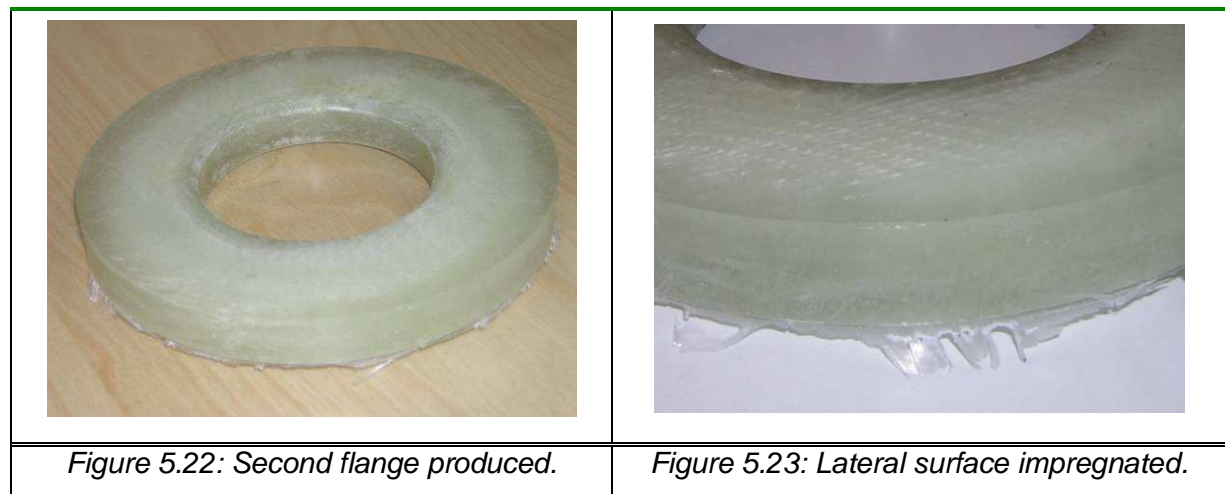


Figure 5.21: Not impregnation.

The figure 5.20 shows a good general vision, but in the figure 5.21 it can be seen as the lateral surface is not impregnated. It is hoped that the resin occupies the channel, because the channel is free of glass fibre. Afterwards, the lateral surface becomes smooth, but it does not happen.

Two main reasons could have influenced. The first one is that the injection pressure of 1,5 bars is too high to impregnate all the layers of glass fibre or that the filling process is too fast. That could be solved by decreasing the injection pressure and thus allow the fluid to flow more slowly in the mould cavity and have more time to impregnate all the glass fibre. Other possibility could be to stop the injection later to allow a greater circulation of the fluid inside the mould cavity, but always the quantity of mixture has to be controlled in order to avoid the injection of air inside the mould cavity. Actually, this is the second observed reason and in order to solve this problem after a short time that the mixture comes out of the mould cavity through the vent port, the pressure is stopped and the injection and vent tube are closed using screw clamp.

These improvements are used in the second prove and the results can be observed in the figure 5.22 and 5.23. The weave number B is used thus the colour change.



The figure 5.22 shows a perfect and smooth lateral surface.

In the first tests an accumulation of glass fibre at the walls of the inner cylinders and the central cylinder, because the dimensions of the holes are equal to the dimensions of the central and inner cylinders. The main consequence is that the impregnating in this zone is insufficient as can be seen in figure 5.25.



Figure 5.24: Fibre accumulation.



Figure 5.25: Nonimpregnated zone.

In order to avoid the accumulation problem is necessary to increase the cut diameter on the weave of glass fibre, especially in the zone of the chamfer, because there is a greater diameter of the central cylinder and therefore a rise of the inner fibre is produced.

5.8.2.2 Small air bubbles

The first injection test shows the bubbles, which are formed when the resin and the hardener are mixed and as a consequence transferred homogenously to the final loose flange. These small bubbles can be observed easily to backlighting, as shows figure 5.26 with the first loose flange produced and 5.27 with the third loose flange produced.

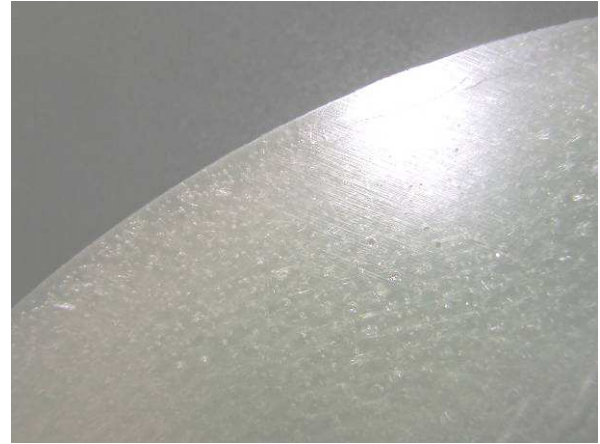


Figure 5.26: First prove small defects.



Figure 5.27: Second prove small defects.

In order to avoid the presence of these small air bubbles one must use a mixing method that avoids the turbulences of the resin and the hardener during the mixing process. Therefore a system using a mixed system less manual is used as can be seen in the figure 5.28.

*Figure 5.28: Mixing System.**Figure 5.29: Fourth prove small defects.*

The results using these methods decrease the amount of small air bubbles, but they not eliminate them absolutely as can be seen in figure 5.29. Therefore the mixture is introduced in a vacuum machine in order to eliminate all these small air bubbles. This method allows to eliminate the majority of these bubbles as can be seen in the photo of the fifth flange produced that appears in appendix number A.4. For this reason the next proves should introduce the mixture in the vacuum machine before the injection process.

5.8.2.3 Air bubbles of the filling process

Some of the produced loose flanges have an air bubble in the vent port zone as can be seen in figure 5.30 and 5.31. In fact this defect confirm that the injection strategy of the injection is correct and that is necessary to improve the tests to avoid these defects.

*Figure 5.30: Third prove air bubble.**Figure 5.31: Second prove air bubble.*

The main reason is that the injection pressure is stopped when the mixture begins to leave the cavity instead of allowing the fluid can fill the cavity during more time. The test number 4 reveals a great circulation of the resin inside the mould allow to avoid these air bubbles as show figure 5.32 and 5.33.



Figure 5.32: Fourth prove.



Figure 5.33: Without air bubble.

Although it is hope that using this system consumes more resin and thus the mixture of the recipient has to be controlled in order to avoid that it will be total consumed. In this case, air would be injected inside the mould cavity.

So far the external air bubbles have been analyzed. It is also necessary to examine if internal air bubbles exist, therefore the loose flange of the fourth prove is cut in different parts. Figure 5.34 shows the loose flange cut.



Figure 5.34: Fourth prove.



Figure 5.35: Without internal air bubble.

In figure 5.35 it is possible to observe as there exist any big internal air bubble but some small air bubbles exits. These small air bubbles come from the mixing method as it has been described. This defect disappears when the resin and hardener are mixed in the emptiness as can be seen in prove number 5 in appendix A.4.

5.8.3 GFV checking

The glass fibre volume can be checked using a simple method. The method of comprovation has the following steps:

First one or more samples or pieces of the loose flange have to be cut as can be seen in figure 5.35. After that the weight of one part has to be measured.

In order to determinate the density of this cut part of the loose flange an empirical method is used. This method calculates the density using a practical montage which is based on the variation of the water when the small part is introduced in a water recipient as figure 5.38 shows. This method uses also a empirical formula and values as could be seen in the next point.

Therefore the method is based on the Buoyancy, which is the upward force on an object produced by the surrounding fluid in which it is fully or partially immersed, due to the pressure difference of the fluid between the top and bottom of the object. The net upward buoyancy force is equal to the magnitude of the weight of fluid displaced by the body. [Web 4].

After that the small part of the loose flange must be introduced in a furnace of high temperature in order to eliminate the cured resin and to obtain only the glass fibre.

Finally it is possible to calculate the glass fibre volume as a simple percentage.

5.8.3.1 Checking example

In the following example the GFV of one part of the forth loose flange produced is calculated. Although in order to obtain a representative GFV of the total loose flange two different parts of the same loose flange, in this case the forth, as minimum have to be analysed.

Once the weight of the part is measured then the montage of the density measurement is constructed.



Figure 5.36: Density Montage.



Figure 5.37: Water recipient.

The montage includes the steps to realize the calculation of the density using different tables with empirical values and the following formula:

$$\rho = \frac{W(a) \cdot [\rho(fl) - 0,0012(g/cm^3)]}{0,99983 \cdot G}$$

The intermediate values used for the density determination are in the following table for each one of the cut parts of the forth loose flange prove.

Table 5.6: Density Calculation

Description: Two small parts of the forth loose flange prove					
	W(a)	G	T	$\rho(fl)$	ρ
1	14,89	9,66	22	0,9978	1,54
2	17,31	11,09	22	0,9978	1,56
Unit	gr.	gr.	°C	gr./cm ³	gr./cm ³

As can be seen the difference between the density of the two parts is small.

Once the density is calculated then it is possible to introduce the pieces into the furnace in order to eliminate the resin with the objective to determinate the weight of the glass fibre of the part. The figure 5.39 shows the furnace of high temperature and in figure 5.40 can be seen as the resin is eliminated and there is only the glass fibre.

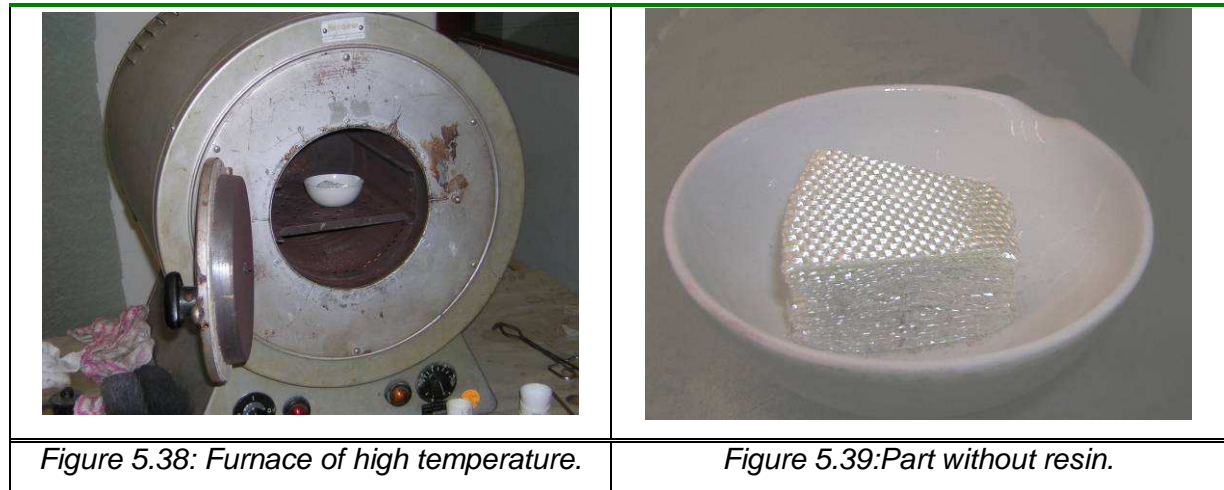


Figure 5.38: Furnace of high temperature.

Figure 5.39: Part without resin.

Thermosetting resin degrades at high temperature around 500°C. Therefore, in order to eliminate this resin the small part has to be heated up enough, and it should be over 600°C. This is a sufficient great temperature to degradate the resin as can be seen in figure 5.38.

Table 5.7: GFV Calculation

Description: Two small parts of the forth loose flange prove						
	W1	ρ	W2	ρ_2	ψ	GFV
1	14,09	1,54	8,24	2,5	58,48	36,02
2	17,31	1,56	9,50	2,5	54,88	34,24
Unit	gr.	gr./cm³	gr.	gr./cm³	%	%

Where W1 is the weight of the part in grams, ρ the density of the part calculated in the previously step of the method in gr./cm³, W2 the weight of the glass fibre or the part without cured resin in grams, ρ_2 the density of the glass fibre in gr./cm³ and ψ the percentage in

weight of glass fibre in the small part in % (W_2 / W_1). The FVG can be calculated as the following equation:

$$GFV = \frac{\rho}{\rho_2} \cdot \psi$$

In the fourth loose flange produced 90 layers of weave A are used in order to obtain a 40% glass fibre volume. But as can be seen in the table 5.4 the value of the FVG is around 35% so 5% minor. The main reason is that the geometry of the weave is shorter to be able to introduce the channel, with or without glass fibre, and to eliminate the accumulation of the fibre around the central hole and inner holes, which will be a defect in the loose flange.

6. Conclusions

- General Conclusions.

6.1 General conclusions

6.1.1 Objectives

The target of this project consists of designing and constructing a prototype of RTM mould for a loose flange of glass fibre reinforced plastic.

Before the design of the RTM mould has begun two important steps have been analysed: the permeability experiments of the glass fibre reinforcement and the simulation of the filling process of the loose flange. Both steps have been made in order to obtain an effective and optimal design of the RTM mould.

The project has begun with the permeability experiments of the glass fibre in order to use an adequate permeability in the simulation. The experiments consist of using a simple equipment and calculation process to obtain a correct permeability value. The simulations of the filling process of the loose flange has been the second step of the project. The simulation allows to visualize the filling process of a 3D loose flange model and to choose the optimal injection strategy analysing different variable of the RTM process such as the viscosity of the resin, the permeability of the fibre reinforcement, the pressure of injection, the distribution of the injection and vent ports, the time of filling, the geometry of the flange and the volume of glass fibre. The next step has been designing the RTM mould using the studies previously described. In this step different aspects of the RTM mould have been described such as the material of the mould, how to realise the loose flange geometry and specifically the central and the inner holes, the realisation of the injection and vent ports, the different parts of the mould and the closing system. After the optimal solution has been chosen the mould designed has been presented and discussed with the operators of the factory in order to obtain the final RTM mould solution, always with the objective of obtaining the maximum quality for the loose flange and the more economic and simple solution for the RTM mould. The RTM mould has been constructed with the modifications realised in the different meetings. Finally the proves of the mould to obtain the loose flange have been realised using an epoxy resin and three different glass fibre weaves. During these proves some parameters such as the pressure of injection, the fibre reinforcement, the mixture between the resin and the hardener have been changed in order to eliminate some defects as non-impregnation zones and air bubbles in the loose flanges produced.

The main objectives have been reached:

- A RTM prototype mould able to produce correctly loose flange with a good quality.
- Low cost of the mould construction and easy to construct.
- A simple injection strategy able to produce loose flange only with one injection and vent port, and also the lower filling time.

6.1.2 Improvements

The following aspects need to be improved in order to obtain a great quality of the loose flange.

- An improvement of the cutting process will provide a time reduction of the positioning of the glass fibre in the mould, an improvement of the filling process, a reduction of the defects in the loose flange, a reduction of later mechanisation and an increase of the mechanical properties.
- An improvement of the mixing process will provide a decreasing of the small bubbles in the loose flange.
- Using a resin which can cure quickly (less than 13 hours) the manufacturing time of the loose flange will be reduced and the analysis of the filling time will be justified and will have more importance that it has until now.
- Improvement in the permeability studies will provide more exact permeability values.
- An accurate analysis of internal defects and mechanical properties will help to improve the manufacturing process and the RTM mould.

Appendix

- ❑ Fibre reinforcement.
- ❑ Resin and hardener.
- ❑ Different parts of RTM mould.
- ❑ Prove Results.

A.1 Fibre reinforcement

A.1.1 Weave A

► Lieferübersicht

Artikel-Nr.	Produkt-Bezeichnung	WLB-Nr.	Gewicht g/m²	Webart	Dicke mm		Fadenzahl Kette/Schuß	Garnfeinheit	
					trocken	im Lamin.		Kette	Schuß
03G025LH	106		25	Leinwand			22 x 22	EC5,5	EC5,5
03G049LH	1080/2037		49	Leinwand			24 x 19	EC5-11	EC5-11
03G080LI	90070	8.4505.60	80	Leinwand	0,10	0,07	12 x 11,5	EC9-34Z	EC9-34Z
03G080LH	235		80	Leinwand	0,10	0,07	12 x 12,5	EC9-34	EC9-34
03G105KI	91110		105	Köper	0,14	0,10	24 x 23	EC5-22S	EC7-22Z
03G163LI	92100		163	Leinwand	0,23	0,15	6 x 5,8	EC9-136Z	EC9-136Z
03G163LI	92105	8.4515.60	163	Leinwand	0,18	0,15	12 x 11,5	EC9-68Z	EC9-68Z
03G163KI	92110	8.4548.60	163	Köper	0,18	0,13	12 x 11,5	EC9-68Z	EC9-68Z
03G163KH	1039		163	Köper	0,18	0,13	11,8 x 11,5	EC9-68	EC9-68
03G200LI	92112		200	Leinwand	0,20	0,18	8 x 6,5	EC9-136Z	EC9-136Z
03G200LH	1266		200	Leinwand	0,20	0,18	8,9 x 6	EC9-136	EC9-136
03G220LI	92145	8.4520.60	220	unidirekt.	0,25	0,19	6 x 7	EC9-340tO	EC7-22Z
03G280LI	92115		280	Leinwand	0,30	0,25	7 x 6,5	EC9-204tO	EC9-204Z
03G280KI	92125	8.4551.60	280	Köper	0,35	0,25	7 x 6,5	EC9-204tO	EC9-204Z

[Web 2] The weave A is the 92112 glass fibre.

A.1.2 Weave B

Artikel	Gewicht	Bindung	Breite
HP-T390EF	390 g/m²	Köper	100 cm

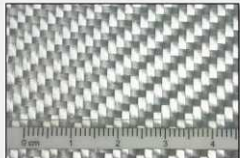

Preis	ab 1m²	ab 5m²	ab 10m²	ab 25m²	ab 50m²	ab 100m²
€/m²	8,03	7,50	6,96	6,43	5,62	4,56
netto	6,76	6,30	5,85	5,40	4,72	3,83

Größere Mengen und Projektpreise erhalten Sie auf Anfrage

Fragen?/Bestellen?

Anwendungsgebiete:
 Modellbau, Sportgerätebau,
 Bootsbau, Kfz-Teile, Formenbau, Behälterbau

Rechnerische Daten für Handlamine
 mit 35% Faservolumenanteil
 Harzverbrauch: 320 g/m²
 Laminatdicke: 0,34 mm
 Laminatgewicht: 710 g/m²

[Web 1]

A.1.3 Weave C

Artikel	Gewicht	Bindung	Breite
HP-P800E	800 g/m ²	Leinwand	130 cm

Preis	ab 1m ²	ab 5m ²	ab 10m ²	ab 25m ²	ab 65m ²	ab 130m ²
€/m ²	4,33	3,71	3,34	2,98	2,48	2,23
netto	3,64	3,12	2,81	2,50	2,08	1,87

Größere Mengen und Projektpreise erhalten Sie auf Anfrage

Fragen?/Bestellen?

Anwendungsgebiete:
Bootsbau, Formenbau, Behälterbau

Rechnerische Daten für Handlamine
mit 35% Faservolumenanteil
Harzverbrauch: 658 g/m²
Laminatdicke: 0,88 mm
Laminatgewicht: 1458 g/m²




[Web 1]


A.2 Resin and Hardener

A.3 Parts of the mould

A.4 Prove Results

Results of Prove Number 1.

Prove Characteristics						
Weave of glass fibre	Channel with fibre	Volume Injected	Injection Temperature	Injection Pressure	Mould Temperature	
A / 90 units	NO	500 g. Resin 120 g Hardener	30 °C	0.5 bars	40 °C / 3 h. 60 °C / 10 h.	
Filling Time			Prove Defects			
Filling Time	Filling Process	General Appearance	Tolerance	Surfaces	Air Bubbles	Others
	x	x	✓	✓	✓	-
Defects Description						
Filling	<ul style="list-style-type: none">○ The resin circulates through the injection tube has the presences of air bubbles which can provoke internal and external air bubbles defects.○ The closing pressure of 30 bars in the press is not sufficient, because there are little waste of the mixing between the different parts of the mould. This aspect can provoke the presence of air bubbles and zones without impregnation.○ When the injection and vent tube are disconnected after the injection process and during the curing reaction both tubes have one lateral not covered, therefore the air can be introduced inside the mould cavity.					
	Air Bubbles	<ul style="list-style-type: none">○ There exist some little bubbles of air around the perimeter of the loose flange and between the layers of glass fibre.				

Surfaces	<ul style="list-style-type: none"> ○ The upper and the bottom surface presents a good finished, but the lateral surface presents irregularities of the impregnation and cavities of air all around the circle.
Photo Flange.	
	

Results of Prove Number 2.

Prove Characteristics						
Weave of glass fibre	Channel with fibre	Volume Injected	Injection Temperature	Injection Pressure	Mould Temperature	
B / 46 units	NO	500 g. Resin 120 g Hardener	30 °C	0.5 bars	40 °C / 3 h. 60 °C / 10 h.	
Filling Time		Prove Defects				
Filling Time	Filling Process	General Appearance	Tolerance	Surfaces	Air Bubbles	Others
9 min.	✕	✓	✓	✓	✓	-
Defects Description						
Filling	<ul style="list-style-type: none">○ The injection process has a little waste of resin. A great clousing pressure can be solve this problem.					
Air Bubbles	<ul style="list-style-type: none">○ There exist some little bubbles of air around the perimeter of the loose flange and between the layers of glass fibre.					
Surfaces	<ul style="list-style-type: none">○ The upper and the bottom surface presents a good finished and the lateral have a good surfaces.					
Photo Flange.						



Second flange produced.

Results of Prove Number 3.

Prove Characteristics						
Weave of glass fibre	Channel with fibre	Volume Injected	Injection Temperature	Injection Pressure	Mould Temperature	
A / 47 units	NO	500 g. Resin 120 g. Hardener	30 °C	0.5 bars	40 °C / 3 h. 60 °C / 10 h.	
Filling Time			Prove Defects			
Filling Time	Filling Process	General Appearance	Tolerance	Surfaces	Air Bubbles	Others
11 min.	✕	✕	✓	✓	✕	-
Defects Description						
Filling	<ul style="list-style-type: none">The resin circulates through the injection tube has the presences of air bubbles which can provoke internal and external air bubbles defects.					
Air Bubbles	<ul style="list-style-type: none">There exist a big air bubble near of the vent port. The main reason is that the circulation of the mixture through the mould cavity is stopped too much early. It has to be stopped after a great time in order to allow that all the air leave the mould cavity.					
Surfaces	<ul style="list-style-type: none">The upper and the bottom surface presents a good finished, but the lateral surface presents irregularities of the impregnation and cavities of air all around the circle. The surface becomes better when the holes of the fibre are great, because then there are not accumulation around the centre hole and inner holes.					



Third flange produced.

Results of Prove Number 4.

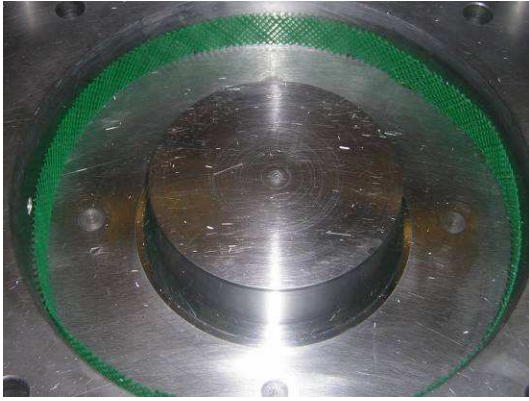
Prove Characteristics: Flange with holes and without fibre in the channel.						
Weave of glass fibre	Channel with fibre	Volume Injected	Injection Temperature	Injection Pressure	Mould Temperature	
A / 90 units	NO	500 g. Resin 120 g Hardener	30 °C	0.5 bars	40 °C / 3 h. 60 °C / 10 h.	
Filling Time			Prove Defects			
Filling Time	Filling Process	General Appearance	Tolerance	Surfaces	Air Bubbles	Others
8 min.	x	x	✓	x	✓	-
Defects Description						
Filling	<ul style="list-style-type: none">○ In order to eliminate the air bubbles near of the vent port a great circulation of the resin inside the mould cavity is allowed. The consequence is that this system consumes more mixture and with 500 gr. of resin is not sufficient. Therefore the resin of the injection is consumed and consequently air is injected. So the air near of the vent port is eliminated but air comes in the injection port zone. The solution is using more resin.					
Air Bubbles	<ul style="list-style-type: none">○ There exist some little bubbles of air around the perimeter of the loose flange and between the layers of glass fibre.					



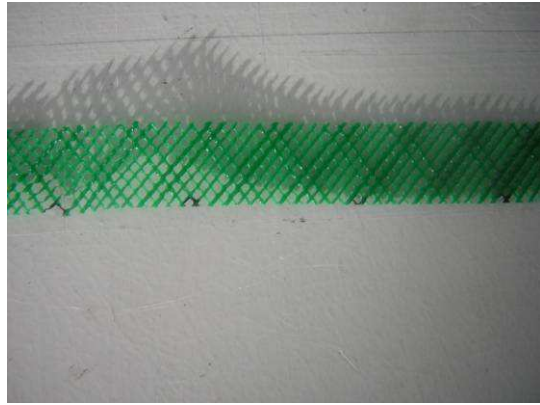
Fourth prove.

Results of Prove Number 5.

Prove Characteristics: Flange without holes and channel using a high permeability fibre.					
Weave of glass fibre	Channel with fibre	Volume Injected	Injection Temperature	Injection Pressure	Mould Temperature
C / 30 units	YES	600 g. Resin 144 g Hardener	30 °C	0.5 bars	40 °C / 3 h. 60 °C / 10 h.
Filling Time			Prove Defects		
Filling Time	Filling Process	General Appearance	Tolerance	Surfaces	Air Bubbles Others
10 min.	✗	✓	✓	✓	✗ -
Defects Description					
Air Bubbles	<ul style="list-style-type: none"> There exist some air bubbles near of the vent port. In this prove 100 gr. more of resin are used in order to allow a great circulation of the mixture inside the mould cavity. Although the result indicates that the vent port is completely fill of air instead of resin, therefore there are air which is not evacuated. In fact in the first prove using a pressure of 1,5 bars all the air near of the vent port leave the mould cavity, therefore in the next proves the following conditions should be used: more resin and more pressure in order to avoid big air bubbles. The are any small air bubbles because the vacuum machine is used before the injection. 				
Channel	<ul style="list-style-type: none"> The presence of the fibre in the channel makes difficult the flow of the mixture, although is a high permeability fibre. 				



Channel with fibre.



Low porosity fibre.



Fifth loose flange produced

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- [Web 4] <http://www.wikipedia.com/>
- [Web 5] <http://www.warwick.ac.uk/>