Experimental process pressure analysis for model-based manufacturing of composites by resin transfer moulding

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Abstract. An experimental study of the process pressure characteristics prevailing in an RTM mould during the preform impregnation stage is presented. The pressure data is analysed with respect to a superposition of preform compaction and hydraulic fluid pressure. A methodology is proposed to isolate the hydraulic fluid pressure from the preform compaction pressure involving knowledge about the compressibility behaviour of the reinforcing material. For this purpose, the preform compressibility and relaxation behavior was studied by means of transverse compaction tests on both, unsaturated as well as the saturated sample stacks. The resulting isolated hydraulic fluid pressure is finally compared with numerical predictions derived from flow simulations, revealing good overall agreement. The findings of this work will contribute to realize the concept of model-based processing of fibre-reinforced polymer composites by means of the RTM process.

1. Introduction
Model-based manufacturing of fiber-reinforced polymer composites is based on transferring process-related knowledge from the level of process modelling to the level of active process management. This requires fundamental understanding of the most significant process-related mechanisms in terms of phenomenological models. In the resin transfer moulding (RTM) process, these can be identified as: (i) preform compaction, (ii) preform impregnation and (iii) resin curing [1, 2].

In the preform impregnation stage, when the viscous fluid saturates the preform material, two effects occur at the location of the flow front: a decrease of the preform compaction pressure due to the wetting of the reinforcing material (i.e. lubrication effects) as well as an increase of the hydraulic fluid pressure as the flow front advances. When sensing the in-mould pressure characteristics with pressure sensors during the preform impregnation stage, a superposition of these two effects contribute to the pressure signal. In order to fully exploit the acquired measurement data, the temporally changing interaction of these two contributors needs to be understood. The driving mechanisms are well known to the composites processing community [3–6] and were extensively treated in a recent review paper [7]. However, despite considerable efforts towards modelling of the compaction behavior of reinforcing materials have been made in the past, preform compliance still needs to be characterized by means of experimental techniques [8–13]. On the level of processing composite materials by means of the RTM technique, the process pressure characteristics can be monitored as a part of process documentation. In addition, they can be involved in active process management to support the concept of model-based composite processing. The paper at hand focuses on an experimental process pressure analysis to provide reliable input data for such a process control task.
2. Experimental Work

2.1. Materials

2.1.1. Test Fluid
The experiments described in this paper were realized with plant oil used as test fluid showing a density of about 920 kg/m² and a dynamic viscosity of about 65 mPas at room temperature (23 °C). The actual viscosity-temperature-characteristics of the test fluid were determined with a Couette rheometer system prior to the experimental series.

2.1.2. Reinforcing Materials
The experimental investigations presented in this paper were elaborated on a glass woven fabric (twill 2/2) of type Hexcel HexForce 1202 (see Figure 1) with a nominal areal weight of 0.29 kg/m². Its in-plane permeability as well as out-of-plane compressibility characteristics were determined experimentally as described in the subsequent section.

![Figure 1. Close-up view of the glass fiber twill woven fabric used for the experiments.](image)

2.2. Material Characterization

2.2.1. In-Plane Permeability
The in-plane permeability characteristics of the glass fiber twill woven fabric were characterized experimentally by means of a testrig following the radial flow method. There, the stack of material layers is placed in a mould and impregnated through a central injection opening. The flow front was tracked by means of eight linear capacitive sensors as described by Grössing et al. [14], which are embedded in the lower part of the mould as shown in Figure 2.

![Figure 2. In-plane permeability characterization system mounted to a hydraulic mould carrier (left). Eight linear capacitive sensors are embedded in the lower mould half (right), arranged in a star-like scheme around a pressure point sensor and opposite to the central injection opening.](image)
2.2.2. Out-of-Plane Compressibility
The out-of-plane compressibility behaviour of the glass fiber twill woven fabric was experimentally characterized with the setup depicted in Figure 3, which is mounted to a universal testing machine. Stacks of the material layers, 60 x 60 mm in dimension, are placed on the pot-shaped pressure plate and compressed against the stamp when moving the crosshead of the testing machine. During the experiment, stack height as well as compaction force are continuously measured by means of a Linear Variable Differential Transformer (LVDT) mounted close to the sample stack and the load cell of the testing machine, respectively. Evaluating the stack height and compaction force data, the characteristics of compaction pressure against fiber volume fraction can be derived. The setup allows for investigating the loading/deloading characteristics of the material under test as well as the relaxation behaviour which is of particular interest for the RTM process. In addition, the tests can be run with unsaturated as well as saturated sample stacks in order to study the impact of wetting on the out-of-plane compressibility behaviour.

![Figure 3. Test equipment for out-of-plane compressibility characterization.](image)

2.3. Manufacturing of Flat Composite Plates by means of Resin Transfer Moulding

2.3.1. Experimental RTM Processing
For the work at hand, RTM process pressure characteristics were studied by means of an RTM mould with dimensions of 270 x 270 x 2 mm. It provides seven openings in the upper part of the mould allowing for a flexible mounting of sensors as shown in Figure 4. The test fluid or chemically reactive resin system can be injected either from one of the side edges of the plate (resulting in linear flow front advancement) or through the central opening in the upper part of the mould (resulting in radial flow front advancement). For the experiments discussed in this paper, linear flow tests were realized, whereas the test fluid was injected by means of a pressure pot with an injection pressure set value of 0.4 MPa. A fiber volume fraction of about 51 % was realized by placing nine layers of the glass fiber twill woven fabric described in Section 2.1. inside the mould. The preform was then impregnated with the test fluid and the process pressure characteristics were captured by means of three pressure point sensors mounted along the desired flow path (see Figure 4). These pressure characteristics were finally studied in terms of partitioning the contributions of preform compaction pressure and hydraulic fluid pressure, both varying with location and experimental time.
Figure 4. CAD design of the RTM mould for manufacturing composite plates (left) showing openings for integration of sensors in the upper part of the mould (right).

2.3.2. Flow Simulation
In the composites processing community, it is commonly accepted to model the fibrous preform material as porous media and the flow of fluids through the preform according to Darcy's law [2, 15, 16], a simple mathematical model relating the flow velocity to the driving pressure gradient involving the dynamic viscosity of the fluid as well as the permeability of the reinforcing material [17, 18].

For the work presented in this paper, numerical flow simulations were run on a model of the RTM mould cavity shown in Figure 4. The preform was modelled by means of nine layers representing the materials layers. Both, permeability of the reinforcing material and dynamic viscosity of the test fluid used for the mould filling tests were characterized experimentally as described in the results section of this paper. Further details about the numerical flow simulations are omitted here due to space limitations for this paper.

Supplementing information about the mould filling trend and the overall mould filling time, the fluid pressure characteristics at the location of the pressure point sensors in the RTM mould were extracted as major results of the numerical flow simulations runs.

3. Results

3.1. Test Fluid Viscosity
As shown in Figure 5, the temperature dependent viscosity characteristics of the test fluid were characterized between 10 °C and 35 °C, a range relevant for experiments at conventional laboratory conditions. In this temperature range, the viscosity characteristics decrease from about 0.10 Pas to about 0.04 Pas following a slightly nonlinear trend.
3.2. In-Plane Permeability
The glass fiber twill woven fabric was characterized at three levels of nominal fiber volume fraction in the range of 0.45 to 0.53 with five repetitions at each level. Plotted at logarithmic scale against fiber volume fraction, the major and minor in-plane permeability data $k_1$ and $k_2$, respectively, follow linear trends as shown in Figure 6.

3.3. Out-of-Plane Compressibility
The glass fiber twill woven fabric was experimentally characterized with respect to its out-of-plane compressibility in the dry, i.e. unsaturated, and saturated state. For both of the two configurations, ten material stacks, each comprising nine layers of the material, were tested in order to add statistical significance to the resulting data. For the experiments in the saturated state, the sample stacks were wetted in a pot of test fluid for three minutes, followed by a dripping period of five minutes. All of the material relaxation tests were run with the following test parameters:
in the compaction stage, the material was loaded with a compression speed of 1 mm/min until a final stack height of 2 mm (which is in line with the situation in the RTM mould and corresponds to a fiber volume fraction of about 51 %) was reached and

- in the relaxation stage, the stack height was frozen for a period of 10 minutes in order to study the internal stress relaxation characteristics of the material.

Figure 7 shows the trends of dry and wet compaction pressure with respect to experimental time in terms of average data together with the minimum and maximum envelopes, respectively, from each set of ten experiments.

![Figure 7](image)

**Figure 7.** Relaxation characteristics of the glass fiber twill woven fabric stacks as plots of average unsaturated and saturated compaction pressure together with the associated confidence envelopes.

The result plots shown in Figure 7 clearly reveal the decrease of compaction pressure as a result of wetting the woven fabric with the test fluid. The average and standard deviation values of maximum as well as final compaction pressure are collected in Table 1.

| material state | max. compaction pressure, [MPa] | final compaction pressure, [MPa] | compaction pressure reduction, [MPa] |
|----------------|---------------------------------|----------------------------------|-------------------------------------|
|                | mean | std. dev. | mean | std. dev. | mean | std. dev. |
| dry            | 0.171 | 0.016     | 0.143 | 0.013     | 0.028 | 0.004     |
| wet            | 0.085 | 0.008     | 0.063 | 0.005     | 0.022 | 0.003     |
| drop           | 0.085 (50.1 %) | 0.080 (55.7 %) | 0.006 (21.4 %) |

Comparison of the average maximum and final compaction pressure in the dry and wet material state reveals a drop of about 50 % and 56 %, respectively, caused by the wetting. This level of relative compaction pressure drop was used for analyzing the process pressure characteristics as will be described in the subsequent section.
3.4. Analysis of RTM Process Pressure Characteristics

In Figure 8, process pressure characteristics are shown as acquired by means of three pressure point sensors mounted to the RTM mould described in Section 2.3.1. From these characteristics, the stages of preform compaction (due to closing of the RTM mould) and preform impregnation can be separated.

During the preform compaction stage, an increase of compaction pressure can be observed which reaches a steady level for all of the three sensors. However, the distinct compaction pressure levels vary among the sensors as a result of local preform inhomogeneity: locations of fiber bundle crossing points obviously show significantly higher levels of preform compaction pressure as regions in between such crossing points.

In the preform impregnation stage however, the three sensors show strongly varying pressure characteristics. The first pressure sensor, which is saturated by the test fluid immediately after starting fluid injection, shows a rapid increase of the pressure data which results from the fluid injection pressure level dominating over the preform compaction pressure. The other two pressure sensors show different characteristics: At first, a slight and steady decrease of the signal can be observed, which is attributed to capillary effects causing partial wetting of the preform at the location of the sensors. This is followed by a rapid decrease of the pressure signal as soon as the macroscopic flow front reaches the location of the sensor. Following this short period of preform wetting, the pressure signal increases as the flow front advances further towards the location of the vents. As soon as the fluid reaches the vents, another rapid increase of the pressure signal can be observed. Here, backpressure is building as a result of increased flow resistance inside the venting tubes. As a result, the amount of pressure increase is highest at the sensor mounted closest to the vents while it is smallest at the sensor closest to the point of fluid injection.

![Figure 8. Process pressure characteristics from pressure point sensors mounted to the RTM mould.](image-url)
As discussed in Section 3.3, preform compaction pressure drops by a factor of $s_{Drop} \approx 0.56$ as a result of wetting of the glass fibre twill woven fabric. This finding can be used to isolate the hydraulic fluid pressure $p_{F,k}$ (index $k$ denoting the number of the pressure sensor, i.e.: $k = \{1..3\}$) from the preform compaction pressure $p_{C,k}$ in the characteristics $p_k$ during the fluid impregnation stage:

- at first, the level of local dry preform compaction pressure $p_{C, dry,k}$ is extracted for each of the three pressure point sensors by calculating the average pressure value from the latest period of data in the preform compaction stage,
- from this, the local pressure drop caused by preform wetting can be compensated from the pressure data acquired during the preform impregnation stage in order to isolate the portion of hydraulic fluid pressure: $p_{F,k} = p_k - (1 - s_{Drop})p_{C, dry,k}$.

Figure 9 shows the isolated fluid pressure data (dashed lines) as a result of compensating the wetting effect from the process pressure characteristics (thin solid lines).

**Figure 9.** Process pressure characteristics during the preform impregnation stage with a compensation of the wetting effect on the preform compaction pressure.

In addition, the resulting hydraulic fluid pressure characteristics can now be compared with fluid pressure data obtained from flow simulation runs as shown in Figure 9. There, the data obtained from the simulation runs (thick solid lines) are in good agreement with the hydraulic fluid pressure data derived from the process pressure characteristics. Although a temporal offset is apparent in the direct comparison of the data, the overall trend as well as the final level of fluid pressure is well comparable. The temporal offset can be attributed to experimental imperfections such as unwanted handling effects on the rather flexible glass fiber woven fabric or race tracking effects along the side edges of the preform inside the mould. However, this is not affecting the validity of the approach presented in this work: RTM process pressure data can be partitioned into their contributions from preform compaction and hydraulic fluid pressure, respectively.
4. Summary and Conclusions
This paper focuses on an experimental analysis of process pressure characteristics acquired in RTM experiments involving a two-sided mould with integrated pressure sensors. The process pressure data acquired with the sensors shows two contributions: the preform compaction and fluid pressure, respectively, both varying with time and location inside the mould. The work reveals an approach for partitioning the fluid pressure from the preform compaction pressure involving a simple model for the preform compaction pressure drop caused by the wetting of the preform material. The amount of compaction pressure drop depends on the fibrous reinforcing material and needs to be experimentally determined by means of compaction tests. The resulting hydraulic fluid pressure characteristics are compared to fluid pressure data predicted by flow simulation, revealing a reasonable level of agreement.

The approach presented in this paper allows for subsequent usage of the isolated fluid pressure characteristics for online computation of fluid flow velocity and its active control following the concept of model-based processing of composites. Future work will concentrate on validating the methodology presented in this paper on other types of preform materials, a study of process parameters as well as tests with chemically reactive resin systems.

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