INFLUENCE OF INACCURACIES IN PERMEABILITY MEASUREMENTS

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Keywords: determination of permeability, fibre volume fraction, pressure gradient, race tracking

Abstract

One of the key factors governing the mould filling in liquid composite moulding (LCM) is the permeability of the preform. To properly simulate the filling process it is therefore necessary to determine it. While software exists to predict the permeability of textiles, measurements are still needed to determine a more reliable value of the preform's permeability. However, as the results of the second permeability benchmark [1] show even with standardised procedures for the measurement of the preform's permeability, the standard deviation at single institutions was up to 51 %. Therefore it is important to investigate possible reasons for these high standard deviations and hence the effects of inaccuracies that may occur during permeability measurements. Factors considered in this work are the areal weight of the fabric, the pressure gradient across the preform and the effect of race tracking.

1. Introduction

Resin transfer moulding (RTM) and other LCM processes gain more and more importance in automotive, aeronautic and many other industries. In RTM a dry fibrous reinforcement is placed into a mould consisting of two rigid mould halves. The reinforcement is either placed as is or after being preformed to the geometrical shape of the final part. The mould is closed and thereby compacts the preform to a defined cavity height. Subsequently a polymeric resin is injected into the cavity between the upper and lower mould half. Once the resin is cured, the finished component can be demoulded. For high-volume production in automated processes, simulation of the injection process can be used to accurately estimate the filling time and necessary clamping force, place the inlet and vents at suitable positions and determine the injection pressure needed. For such simulations the flow through the preform can be described by the following common variation of Darcy's law [2, 3]:

$$v = -\left(\frac{K}{\mu \cdot \phi}\right) \cdot \nabla P \qquad (1)$$

wherein v, μ, ∇P, ϕ, and K are respectively the fluid's velocity, its dynamic viscosity, the pressure gradient across the preform and the preform's porosity and permeability. Currently the most reliable method of determining the permeability is by direct measurement in an experimental setup. However, even with such a setup standard deviations of approx. 20 % can be observed across the participants of a benchmark exercise and up to 51 % within single institutions participating the exercise [1].

2. Setup and procedure

2.1. General setup and procedure

The experiments for this study were conducted using a permeability-testing rig (Figure 1) devised by the Department of Polymer Materials and Plastics Engineering (PuK) of Clausthal University of Technology. It is based on optical tracking of the flow front and facilitates both, one-dimensional (1D) experiments and two-dimensional (2D) experiments. In 1D experiments – as used in this investigation – the flow front starts on one edge of the textile and progresses through it as a straight line (Figure 2). In 2D measurements, the flow starts from a

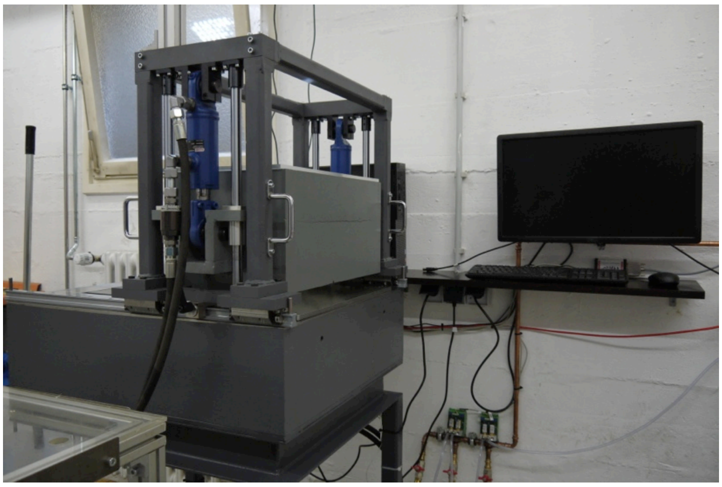

Figure 1. Permeability-testing rig at PuK

central injection point and the flow front progresses elliptically through the fabric. The testing rig features a stiff upper mould made of a steel-beam-reinforced glass plate and lower mould made from a steel block to prevent deflection. Furthermore the cavity is adjustable to any desired height between 1 mm and 10 mm by use of spacer plates made from thickness gauge strips. The mould is closed with two hydraulic pistons attached to a manual pump to build up a closing force of up to 60 kN. These features allow for a very exact definition of the cavity height. In addition, the cavity height is measured ex-post with the help of waxen pellets. They are placed along both sides of the textile as well as at the inlet and outlet (Figure 2). The pellets are compacted to the cavity height by plastic deformation when the mould is closed.
To prevent race tracking and hence achieve a straight flow front through the textile (as seen in

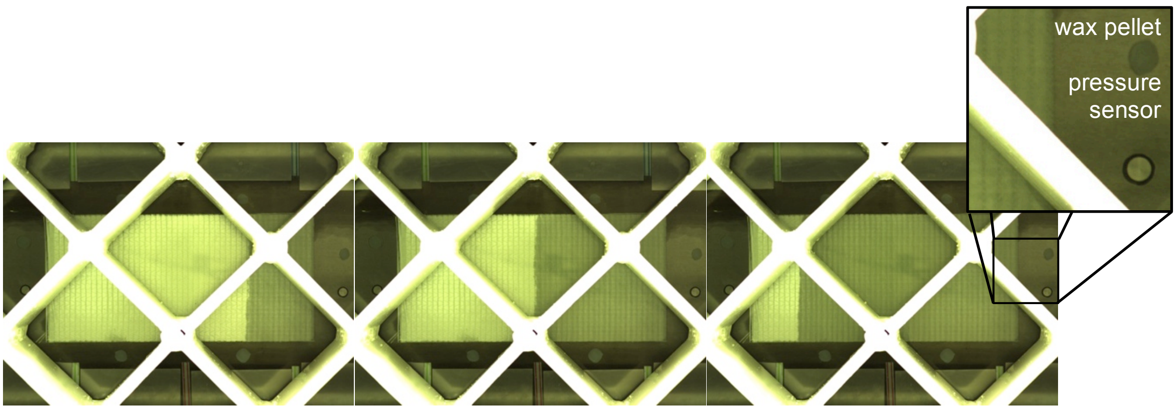

Figure 2. Flow front advancement in a 1D experiment, placement of wax pellets and pressure sensors

Figure 2), the sides of the textile are sealed with a hardening fluid in 1D experiments. This fluid can be adjusted in viscosity and is injected along the edges of the preform after the cavity has been closed. The fluid enters the textile only at the very edge, mainly driven by capillary force. The edges are thereby fully sealed without causing any distortion of the fabric. Pressure and temperature data are collected with the help of sensors, which are located close to the textile edge at the inlet and the vent (Figure 1). The test fluid is a silicone oil with a viscosity of approximately 100 mPa·s (AK100 by Wacker). The temperature dependency of the viscosity is known and the viscosity is corrected according to the temperature present during the experiment.

A proprietary pressure and temperature recording software is used together with an in-house Matlab script to conduct the experiment. The script provides a GUI to carry out the experiment. It sets the injection pressure (0.5–6 bar) and tracks the flow front by grabbing images from a camera with up to 3 fps. It also features an algorithm to detect the flow front online by using difference images. This allows for adjusting the rate of image grabbing to the actual speed of flow front progression. The permeability is then calculated by using the fitted squared flow front approach described in [1].

2.2. Procedure for race tracking measurements

As discussed above, race tacking is generally prevented in the setup. However, part of this investigation is the influence of race tracking on the measured permeability. In an effort to create reproducible race tracking, the preforms were not left without sealing, but rather cut through the middle. The two halves were then handled in the setup the in same way as the normal preforms were (Figure 3). The flow front position used for the calculation of permeability was the one at the edges of the textile, closest to the inlet. Due to the nature of the Matlab script the flow front position was not automatically detected but manually set for each image.

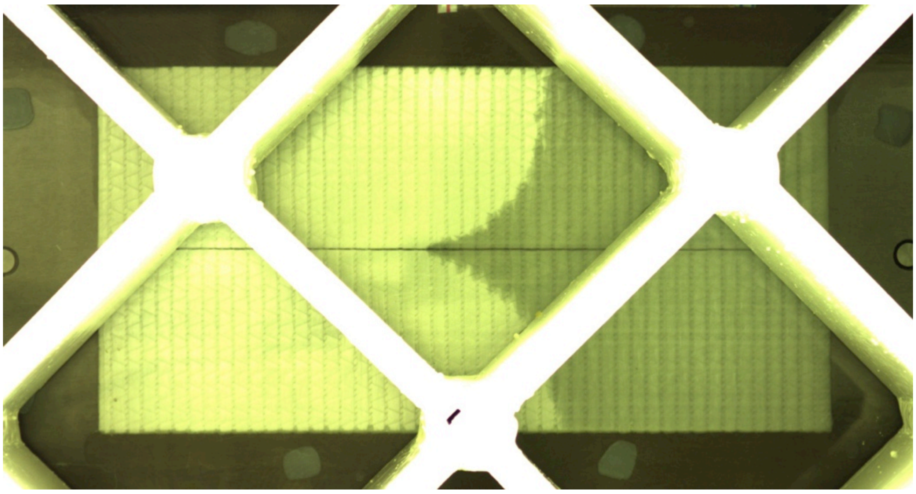

Figure 3. Cut preform to measure the effect of race tracking on the measured permeability

3. Fabrics

The fabrics used in this exercise are a breather veil with an average areal weight of about 160 g/m² (standard deviation: 6.4 %) and S32EQ260, a quadrax glass non-crimp fabric (NCF) with a datasheet areal weight of 822 g/m² and an actual average weight of about 811 g/m² (standard deviation: 0.59 %). The breather was cut to pieces of about 23 cm × 12 cm, while the NCF was cut to pieces of 25 cm × 12 cm. This was done manually with a ruler and a rotary fabric cutter. The final pieces were weighted and their actual dimensions were recorded. They were then stacked to form preforms of three layers. For the glass fibre NCF the permeability was measured for different fibre volume fractions (V_f,) to obtain a fit for the permeability depending on V_f, which is later used as reference for the permeability data.

4. Results and discussion

4.1. Influence of inaccurate areal weight

In Figure 4 the permeability of the breather fabric is plotted against the fibre volume content. In this graph, three approaches of calculating the permeability are plotted: permeability is calculated using the desired V_f, the V_f corrected for the cavity height but using the average areal weight and the V_f based on both, actual cavity height and areal weight for each preform.

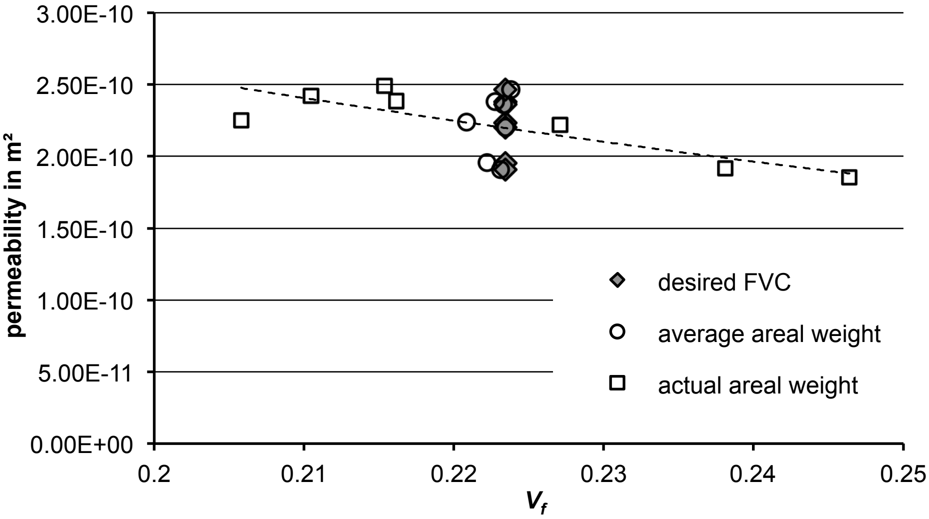

Figure 4. Permeability and V_f (FVC) for the breather fabric

As seen in Figure 4, the areal weight of the breather fabric significantly varies causing the fibre volume fraction to span from 0.206 to 0.246. The standard deviation of areal weight for the used preforms is 6.4 % and is the main reason for the wide spread of fibre volume contents. The cavity heights as measured ex-post only exhibit a standard deviation of 0.42 %. Using an exponential fit, it can be seen, that the measured permeabilities follow the expected trend, when the data is corrected for both, height and areal weight. Much of the scatter observed with the uncorrected data and that, which is only corrected by the actual cavity height, becomes hence explicable. However, while a lot of scatter is observed, the measured permeability at the desired V_f hardly deviates from that of the corrected fit (approx. 1 % deviation).

Figure 5 shows a similar graph for the glass NCF. In this graph an additional plot is presented, in which the permeability is calculated based on the V_f resulting from the datasheet areal weight and the actual cavity heights. The glass NCF has a much more constant areal weight. Its standard deviation is only 0.59 %, and is in the same range as the standard deviation of the cavity height (0.33 %). This also explains the much smaller range of V_f observed in these measurements – spanning from 0.463 to 0.474. While even the corrected data does not nicely follow the exponential trend in this small range, the distribution of values still seems much more plausible than under the assumption of datasheet areal weight and constant heights (desired V_f).

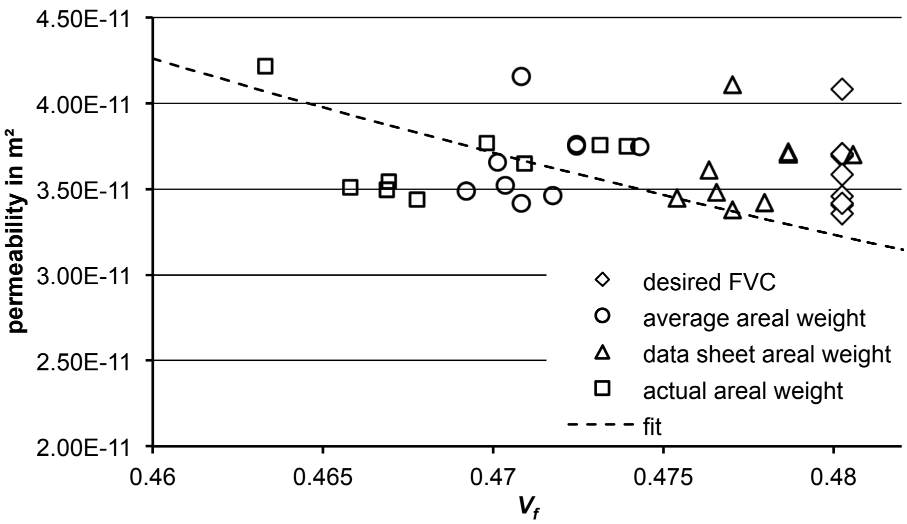

Figure 5. Permeability and V_f for the glass NCF

Furthermore despite the smaller range of V_f covered, the actual error made when using only the desired V_f as basis for the calculation is as big as 12 %. However, the importance of fluctuations of areal weight due to the fabrication process of the fabric is also noteworthy for another reason: The datasheet states a possible fluctuation of 5 %, which is reflected in the V_f. Figure 6 illustrates this, with the red borders defining the range of V_f, which is possibly caused by this effect. The resulting deviation of permeability is approx. +30 % and −23 % for the given fabric. This has to be considered during the manufacture of parts, as this variation strongly influences the injection times needed.

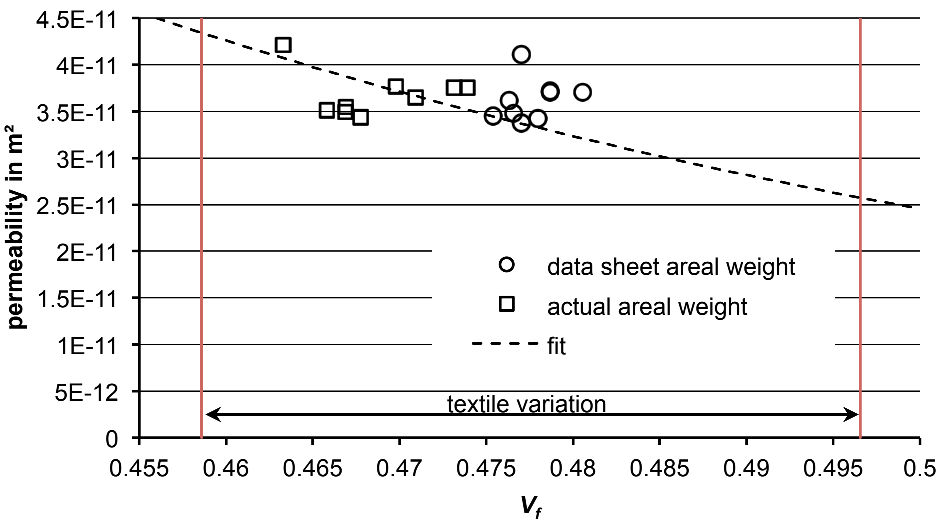

Figure 6. Range of V_f caused by deviation of the fabric's areal weight

4.2. Influence of inaccuracies of pressure control

The influence of inaccuracies of pressure measurement on the observed permeability is equal to the inaccuracies themselves due to the nature of equation 1. Therefore an accurate measurement of pressure right in front of the preform is crucial. However, it has been suggested [4] that the pressure gradient across the preform also influences the measured permeability. To investigate the influence of the pressure drop across the preform, experiments with 0.5 bar, 2 bar and 5 bar injection pressure were conducted to complement the measurements at 1 bar.

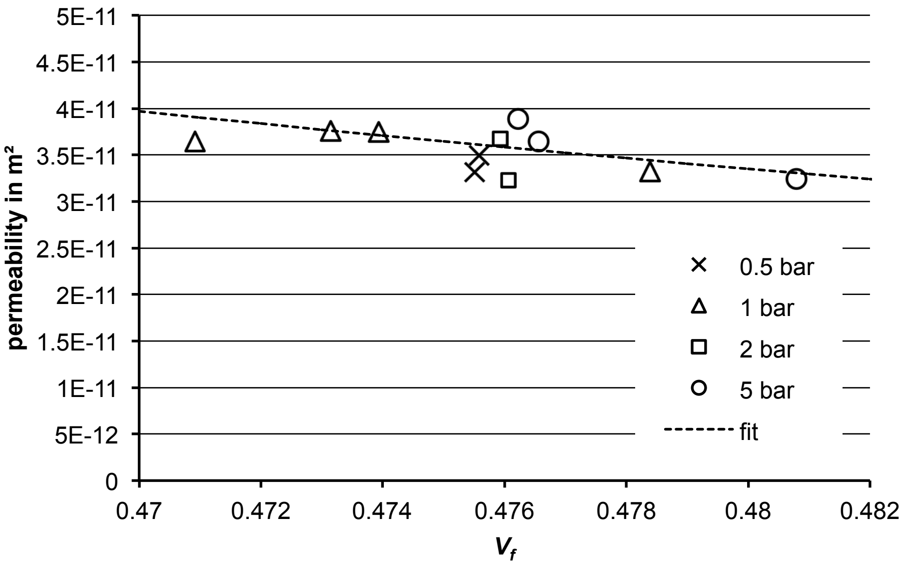

Figure 7. Measured permeability for different injection pressures

For these experiments the glass fibre NCF was used. The results of these experiments are presented in Figure 7. At a pressure different of 5 bar a movement of the preform in the mould was observed during the experiments and caused the need for repetition of some experiments.

Unfortunately the number of performed measurements is not big enough to make a statistically sound general statement on the influence of pressure. It is however obvious that inaccuracies of pressure control do not have a significant effect on the measured permeability.

4.3. Influence of race tracking

While race tracking can be prevented with a setup such as the one described in section 1, it may occur in other setups and is frequently reported. Despite the effort to create reproducible race tracking, the resulting distance between leading edge of the flow front and trailing edge as well as the development of this distance was significantly varying (Figure 8).
The effect of race tracking on the measured permeability is illustrated in Figure 9. It can be seen that race tracking causes a significant overestimation of the actual permeability of a preform. Taking the fit over V_f as reference, the average increase of permeability due to race tracking is about 44 %. Unfortunately a dependency between the average race tracking dis-

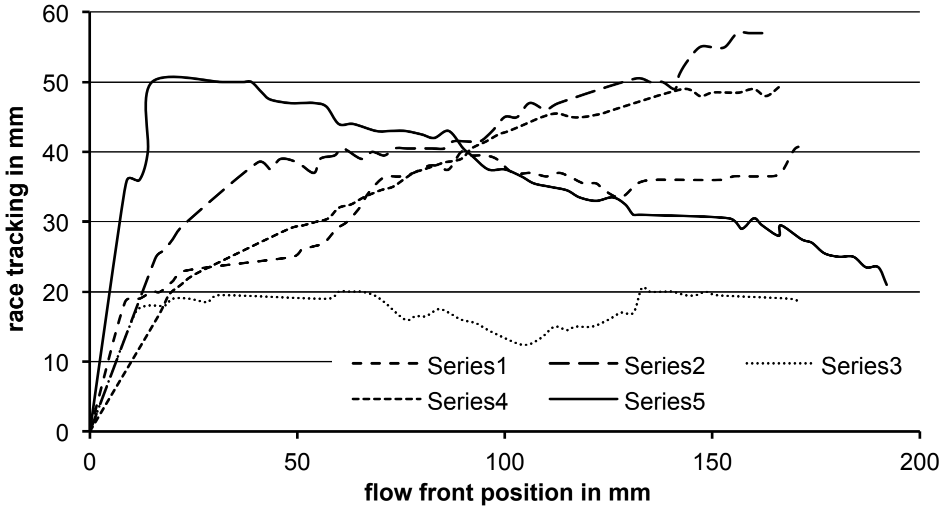

Figure 8. Race tracking distance for the performed experiments

tance and the increase of permeability could not be established with the conducted number of experiments. The importance of preventing race tracking in terms of inaccuracy during the conduction of permeability measurements is however nicely illustrated.

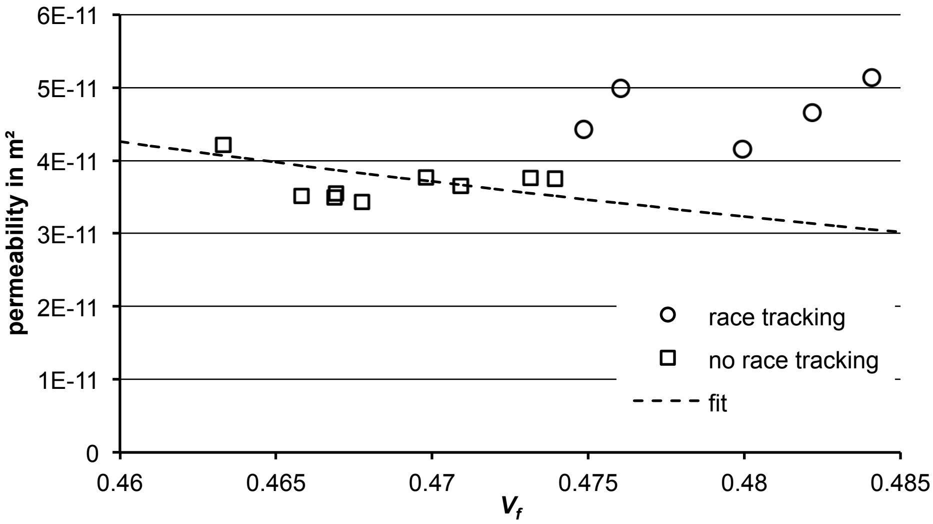

Figure 9. Permeability with and without race tracking

5. Conclusion

This work underlines the importance of closely observing the weight of the preforms used for permeability measurement and the prevention of race tracking. Besides, even with close observation of all factors, a remaining deviation of 4 % to 5 % still occurs. This substantial deviation cannot be attributed to the measurement process only, suggesting that it is mainly caused by preform inherent deviation. The varying areal weight of fabrics furthermore has to be considered in the process design for RTM processes. The range of almost 5 % of V_f as shown above may cause a significant change in permeability and hence influence the filling times. Furthermore race tracking during the experimental procedure causes a significant overestimation of the preforms permeability. Therefore special care has to be put on preventing it by using a setup design such as the one described in section 1.

While the effects of the above inaccuracies are major, no influence of the pressure drop across the preform could be observed. Therefore the requirements for pressure control are not high, as long as an accurate measurement of the pressure drop across the preform is performed.

6. References

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