

CORRELATED PERMEABILITY DISTRIBUTION: MOULD FILLING SIMULATIONS VERSUS EXPERIMENTAL RESULTS

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ABSTRACT: This paper describes the comparison between the simulation results and experiments for a basic liquid moulding process. In the simulation, the uncertainty valid for the permeability of a textile preform is incorporated in a correlated way. Input data for the meso scale correlated permeability distribution is obtained using surface scanning of textile reinforcements. The Monte Carlo implementation of the scatter of the preform permeability allows generating additional information compared to a conventional deterministic simulation software as there are average filling time, standard deviation on the filling time and number of times a certain element is not filled. Starting from a known injection strategy, the number of times a certain element is not filled can indicate the probability to have good parts. On the other hand, the coefficient of variation for the filling time output together with the average filling allows to find the corresponding macro scale permeability scatter. This information is compared with the widely available experimentally observed scatter obtained with the radial injection set-up. The influence of the different parameters describing the meso scale permeability distribution is also investigated. Good correspondence is found between measurements and simulations.

KEYWORDS: Correlated, permeability, stochastic, mould filling simulation, experiment, textile geometry

INTRODUCTION

Nowadays, the RTM process gains a lot of interest to manufacture composite parts. Depending on the textile and the difficulty of the part to manufacture, it is possible to encounter problems with the mould filling. To lower the amount of bad moulds or injection strategies, one uses mould filling simulations to check the filling behaviour. One of the most important parameters in these models are the preform permeability values. In the past, several measurement set-ups were developed to characterize this parameter in an accurate way for different types of textiles under different process conditions. Every researcher ended up with the conclusion to have a reasonably large scatter for the macro scale permeability values. Up to now, mould filling simulations were performed using average permeability values. As scatter can be quite large for the permeability values, unwanted filling patterns are not seen in a deterministic simulation. To avoid this, one has to take into account the scatter for the meso-scale permeability.

Before, it was already proven that it does not make sense to generate a complete random distribution for the permeability as the resulting macro scale scatter is mainly depending on the size of the regions to which the randomly defined permeability values are assigned [1]. For that reason, a correlated approach is used. Before, there was no information available on the standard deviation and the correlation distance for the permeability on a local scale (meso). Within this paper, a technique is described to find data for the meso scale permeability together with the correlation distance. This information is used as input for the stochastic simulation. The outcome of this study is then compared with well-known data on the scatter for permeability at macro scale. As the technique to find the meso scale permeability information is not that tight, the sensitivity of the different parameters is investigated using the developed simulation tool based on PAM-RTMTM software from the ESI-group (France).

CHARACTERIZING THE MESO SCALE PERMEABILITY SCATTER+CORRELATION

To obtain meso scale permeability data, several approaches were tested. Both direct measurement of the flow fronts and statistical modelling of textile architecture did not result in useful data for the meso scale permeability up to now. The tool presented by S. Lomov in this conference opens new possibilities. Another characterisation of the scatter for the permeability in a textile is making a link with a property which can easily be measured. An example of such a property for a woven fabric or a unidirectional material is the channel width. In case of a thin fabric, optical surface scanning can be used. In case of thick fabrics, X-ray μ CT can be used. It is also possible to use this technique for an open channel (for example race-tracking) to define the variability of the channel width together with a correlation for this dimension.

To find the variability together with information about the correlation for thin fabrics, a conventional scanner linked to a desktop computer can be used. It is possible to scan rather large parts of a textile reinforcement (for example 20 x 30 cm). This allows acquiring data in the middle of the textile to avoid too much deformations of the yarn architecture due to cutting and in the regions close to the borders. Of course, it can also be interesting to see what is the influence of the cutting on yarns which are close to the border of the textile. To obtain useful data on the channel dimensions versus position along the channel, the textile has to be scanned with a high resolution to result in accurate information. A resolution of 2000 dots per inch is satisfactory. This corresponds to a measuring resolution of 12.7 μ m/pixel. Within a conventional fabric, for example the fabric used in the experiments of Hoes [2], the average channel width between yarns is 0.5 mm. If no measuring errors are taken into account, the maximum relative error that can be made is 2.5% corresponding to this scan resolution.

Formulas (1) and (2) allow to calculate the correlation valid for a property X.

$$\hat{V}_{x,x}(i\Delta z) = \frac{1}{M} \sum_{j=1}^{M-|i\Delta z|} [X(z_j) - \bar{X}][X(z_j + |i\Delta z|) - \bar{X}] \quad (1)$$

$$i = 0..M - 1$$

$$\hat{R}_{x,x}(i\Delta z) = \hat{V}_{x,x}(i\Delta z) / V_{x,x}(0) \quad (2)$$

To be able to apply the formulas (1) and (2) to find the correlation distance A for a parameter X for M sample points, the measurement of the channel width should occur at a constant distance Δz . As measurements have to be done by hand, one should avoid to

small Δz . A realistic distance for Δz is the average yarn spacing along a certain direction. Afterwards, a control should be done to check if the correlation distance found is large compared to the distance Δz .

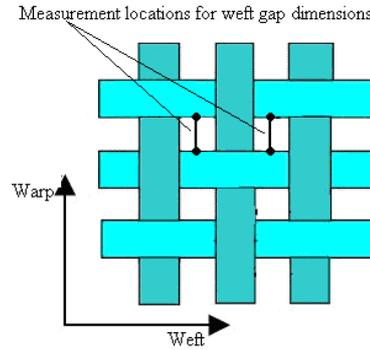


Fig. 1 Measurement location for gap dimensions

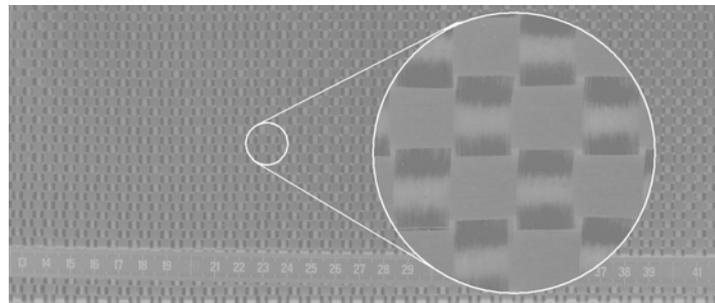


Fig. 2 Example of scanned thin fabric

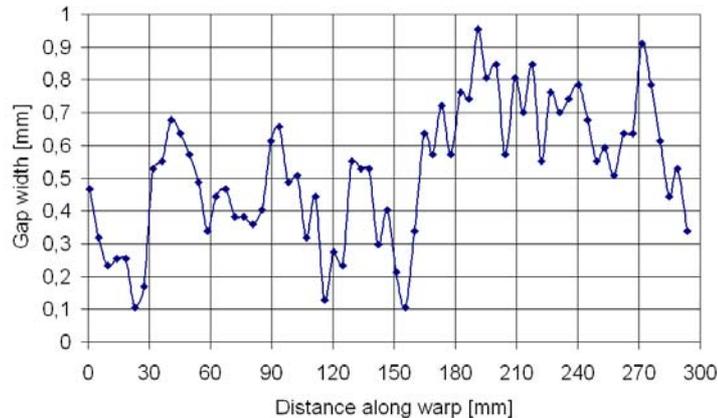


Fig. 3 Example for gap width along warp direction

Fig. 1 shows the measurement locations in case of a plain woven fabric. In Fig. 2 an example is shown of an image acquired with a scanner for the textile used in [2]. For a particular channel, the channel width along the whole scanned length of the fabric is displayed in Fig. 3. From this data, the average value together with the standard deviation can be calculated. This results in a gap width equal to 0.51 ± 0.187 mm (COV = 37%). Using Equations (1) and (2), it is possible to plot the data for the correlation function (Fig. 4). Through this data, a correlation function (Eq. (3)) can be fitted (Least squared error principle) resulting in a correlation distance A to be 1.22 centimetre.

$$R(i \cdot \Delta z) = \exp\left(-\frac{i \cdot \Delta z}{A}\right), i = 0 \dots M-1 \quad (3)$$

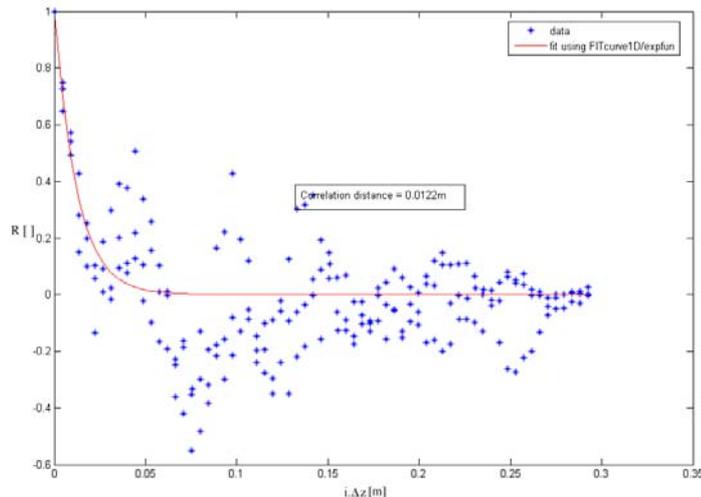


Fig. 4 Correlation function for gap width along warp direction

With this data, the stochastic information for the meso scale permeability can be defined. As permeability depends to the characteristic dimension of a reinforcement in a second order way, the standard deviation for the permeability is twice the standard deviation of the characteristic dimension of the textile reinforcement. In this investigation, a coefficient of variation of 74 % is used along both directions for the meso scale permeability. The correlation distance is kept the same as for the gap dimension as direct relation between the dimension and the permeability is assumed. The average value used for the meso scale permeability in both directions is the average value obtained by the experiments.

DIFFERENT PARTS IN STOCHASTIC SIMULATION

Preparation of the finite element model

To take into account the stochastic effects for permeability in mould filling simulations, the finite element model developed for the deterministic simulation can be used. Within this model, the part can be divided in different master zones depending on the number of textile materials that is used and the part thickness. Before, average data for permeability and other reinforcement parameters is assigned to one master zone. Next to reinforcement data, also information on the boundary conditions (injection, vent,...) can be defined in the usual way. Based on this model, the developed preprocessing program can be used to read the finite element model and to subdivide the different master zones into small sub zones. Within PAM-RTM, only one set of permeability values can be assigned to a zone.

Assigning permeability information

Once the finite element model is available, the meso scale permeability data has to be assigned. This can be done using the covariation decomposition algorithm [3]. To avoid problems with negative permeability values resulting from the normal distribution with a large coefficient of variation, a minimum permeability value has to be defined for each direction. This results in a disturbed normal distribution. To avoid this, the user also has the possibility to use the lognormal distribution. The covariation decomposition

algorithm allows to generate input files for the PAM-RTMTM software in a fast way. For each file, only a new random set of numbers has to be generated and multiplied with the lower triangular matrix resulting from the Cholesky decomposition.

Generation of the input files for PAM-RTMTM

Next to the permeability information, also information on the thickness (for thin shell models), the porosity and the viscosity of the matrix material has to be defined. With the preprocessing program, all this information together with the permeability information valid for one of the files out of the Monte Carlo approach is written respecting the order necessary for the input files for PAM-RTMTM.

The generated input files can be solved one by one in an automated way.

Post-processing

Once all the input files are solved with the PAM-RTMTM solver, the interesting data has to be filtered out. For each input file, PAM-RTMTM has generated a file containing for each element of the finite element model the time for which a certain element starts to fill and the time when it is completely filled. If the resin never reaches a particular element, this element number is not listed. This indicates an air entrapment in this run of the Monte Carlo approach. All these information is stored in memory to be able to access it in an easy way.

For comparison with experimental results, two additional parts were developed within the post-processing program. First of all, it is possible to read in a file containing the coordinates of sensors placed inside the mould. Based on these sensor coordinates, the scatter for the global permeability can be characterized similar to a technique applied within experiments.

Another additional part, is the possibility to fit the flow fronts with ellipses using least square error algorithm. This allows to find the scatter for the macro permeability in another way.

SIMULATION VERSUS EXPERIMENT

Experimental result

In [2], a new set-up to measure the in-plane permeability using central injection technique is described. Using this set-up, he was able to perform measurements in a fast way enabling to find information about the standard deviation valid for the permeability values for textile reinforcements. The set-up used in this investigation is displayed in Fig. 5. On Fig. 5, also the different sensors used to define the macro-scale permeability are recognizable.

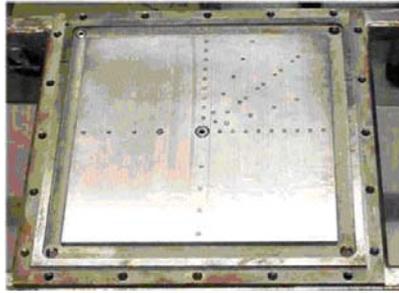


Fig. 5 Sensor based set-up of K. Hoes

For one fiber volume fraction, the obtained data for the permeability on a macro scale is displayed in Table 1.

Table1. Macro scale permeability variation based on sensor approach

Direction	Average value	Standard deviation	COV [%]
Warp	$179 \cdot 10^{-12} \text{m}^2$	$40 \cdot 10^{-12} \text{m}^2$	22
Weft	$144 \cdot 10^{-12} \text{m}^2$	$29 \cdot 10^{-12} \text{m}^2$	20

Simulation result

Based on the technique described to characterize the meso scale permeability parameters, Table 2 gives the values used to perform the stochastic simulation.

Table 2. Meso scale input information for the permeability

Direction	Average value [m ²]	Standard deviation [m ²]	Coefficient of variation [%]	Correlation distance [m]
Warp	$179 \cdot 10^{-12}$	$141 \cdot 10^{-12}$	79	0.0122
Weft	$144 \cdot 10^{-12}$	$114 \cdot 10^{-12}$	79	0.0095

If 150 files were generated using the Monte Carlo approach, the following results (Table 3) were obtained using the information obtained by the sensors. The formulas to obtain the permeabilities along the main axis are given in [4]. Examples of flow front versus time taken from different models within the Monte Carlo approach are given in Fig. 6.

These results show good correspondence to the numbers found during the experiments. In stead of using the sensor approach, also ellipses has been fit through the different flow fronts versus time. With this technique, the center of the ellipse is not forced to be at the injection point. The results for these approach are shown in Table 4. The modeled origin coordinates are 0.15 along both X and Y direction. The values for the permeability also corresponds well to the experimental results.

The influence of the values for the meso scale permeability and the correlation distance is shown in a next paragraph.

Table 3. Simulation result for the macro scale permeability based on sensor approach

Direction	Average value	Standard deviation	COV [%]
Warp	$169 \cdot 10^{-12} \text{m}^2$	$44 \cdot 10^{-12} \text{m}^2$	26
Weft	$131 \cdot 10^{-12} \text{m}^2$	$29 \cdot 10^{-12} \text{m}^2$	22

Table 4. Simulation result for the macro scale permeability using the ellipse fitting approach

Direction	Average value	Standard deviation	COV [%]
Warp	$172 \cdot 10^{-12} \text{m}^2$	$38 \cdot 10^{-12} \text{m}^2$	22
Weft	$139 \cdot 10^{-12} \text{m}^2$	$27 \cdot 10^{-12} \text{m}^2$	19
Xz	0.151 m	0.006 m	4
Yz	0.151 m	0.006 m	4

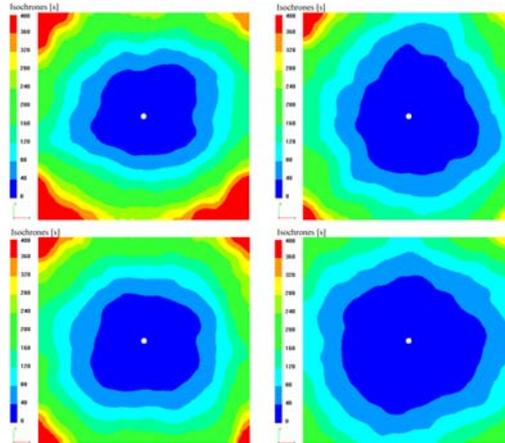


Fig. 6 Examples of flow front positions versus time for different runs from the Monte Carlo approach

INFLUENCE OF DIFFERENT PARAMETERS

To be able to think about the influence of the most important parameters within this stochastic approach, namely the correlation distance and the meso scale scatter for the permeability, an investigation was set up with an average permeability of $200 \cdot 10^{-12} \text{m}^2$ along both warp and weft direction. First, the meso scale coefficient of variation was changed (Figure 7 left). It seems that the relation between the meso scale coefficient of variation and the macro scale COV is more or less linear for a given correlation distance with this set-up dimensions. If a model is built with doubled dimensions, the macro scale COV does not change. The influence of the correlation distance is shown on Figure 7 right. If the correlation distance would be 0 which corresponds to a complete random distribution, the meso scale coefficient of variation would be zero if the zones to which the permeability values are assigned are small. If a large correlation distance is assumed the limit value for the macro scale coefficient of variation would be 75% (= meso scale coefficient of permeability).

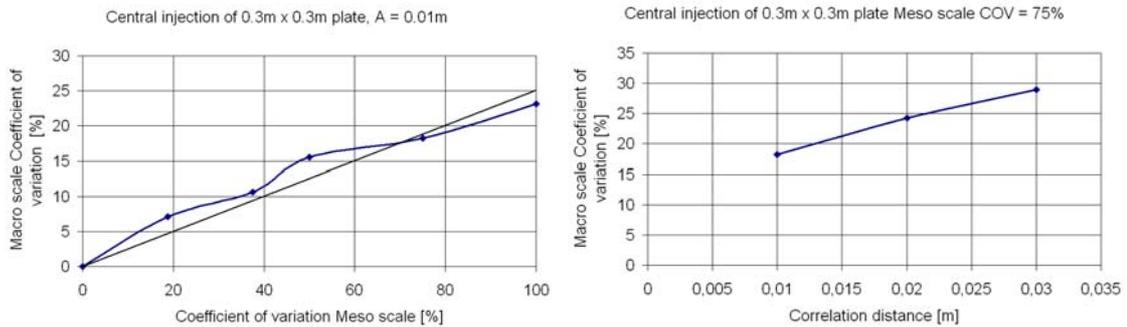


Figure 7. Influences of main parameters on macro scale coefficient of variation for permeability

CONCLUSIONS

With this investigation, it is shown that it is possible to use statistical data within mould filling simulation software in a useful way. Starting from a property which easily can be measured, it is possible to obtain information on the meso scale permeability valid for a certain textile reinforcement type. The investigation on the influences of the different parameters shows the importance of both parameters. Good characterization of the meso scale level coefficient of variation together with the correlation distance is important.

REFERENCES

1. Desplentere, F., S.V. Lomov, and I. Verpoest, *Influence of the scatter of perform permeability on the mould filling: Numerical simulations*, in *Proceedings of the 25th International SAMPE Europe Conference, March 30th - April 1st. 2004*: Paris. p. 331-336.
2. Hoes, K., et al., *New set-up for measurement of permeability properties of fibrous reinforcements for RTM*. *Composites Part A: Applied Science and Manufacturing*, 2002. **33**(7): p. 959-969.
3. Nicolai, B., *Modeling and uncertainty propagation analysis of thermal food processes*, in *KUL. Faculteit landbouwkundige en toegepaste biologische wetenschappen*. 1994, KU Leuven: Leuven.
4. Hoes, K., *Development of a new sensorbased set-up for experimental permeability identification of fibrous media*, in *Faculteit Toegepaste Wetenschappen*. 2003, Vrije Universiteit Brussel: Brussels.