Identification of the effect of typical curvatures encountered in RTM parts on localized permeability of fibrous preforms

Spiridon Konstantopoulos1*, Christian Hueber1, Elisabeth Mühlbachler2 and Ralf Schledjewski1,2

1Christian Doppler Laboratory for Highly Efficient Composites Processing, Otto Glöckel-Straße 2/I, 8700 Leoben, Austria
2Department of Polymer Engineering and Science, Montanuniversität Leoben, Otto Glöckel-Straße 2/III, 8700 Leoben, Austria

Abstract Filling is a critical stage in resin transfer molding (RTM) manufacturing; it is associated to the formation of impregnation imperfections which can lead to defects. Simulations are typically employed to predict the flow behavior, which however need the preform permeability as an input. Significant work has been done in the past in in-plane permeability identification. This study focuses on the determination of the permeability of unidirectional curvatures typically encountered in RTM parts. A model for analytical calculation and a numerical optimization approach for inverse determination have been developed and applied in an omega-shaped RTM part where material-embedded flow sensors were employed for the essential flow measurements. The differences found between the experimentally derived permeability of the curvature and theoretical predictions were discussed critically and associated to flow time disagreements between simulations and reality.

Keywords Permeability, Flow monitoring, Draping

Cite this article Spiridon Konstantopoulos, Christian Hueber, Elisabeth Mühlbachler and Ralf Schledjewski: Adv. Manuf.: Polym. Compos. Sci., doi: 10.1080/20550340.2016.1229829

Introduction

Filling a preform with polymeric matrix by injection, in resin transfer molding (RTM), may lead to filling defects depending on the geometry, the materials, and the thermodynamical conditions.1 Filling simulations based on finite element solution of the governing laws of flow within porous media are a valuable tool for the a priori identification of such defects and have high potential in both material research and process development. However, simulations may differ from reality; poor compatibility between simulation inputs and actual conditions, models that fail to describe accurately the actual behavior and the inherent structural uncertainty of fibrous preforms are the main origins of such differences.2 A decisive input parameter for simulations is permeability; an intrinsic preform characteristic inversely proportional to the flow resistance that the fluid is subjected to by the fibrous preform. Since it is heavily affected by the structural uncertainty of the preform, permeability has been found to vary significantly.3,4 Special instruments have been developed to determine reliable permeability in all three directions. Their operation is based on flow front detection which leads to permeability by a forward calculation of existing flow models.5–7 Alternatively, flow measurements can be utilized by an inverse method; an iterative optimization process where the difference between flow measurements and simulation outputs is minimized by redefining permeability.8,9 Despite the fact that a realistic part includes curvatures and areas of draping, past studies that are using the forward or inverse method focus mainly on in-plane flow behavior. Limited research on the permeability of curvatures has shown that they are characterized by different permeability as compared...
to the same planar preform,

\[ \text{in-plane permeability (theoretical approximation).} \]

Thus introducing yet another possible origin of simulation error.

In this study, the permeability change in typical curvatures of RTM parts was determined both analytically and inversely based on flow time measurements by electrical microwire flow sensors. Appropriate modeling and numerical optimization techniques allowed the above while results were discussed critically with respect to theoretical expectations and simulations.

Method description

Theoretical background

A draping zone within a preform presents a permeability decrease as compared to the planar zone of the same preform due to the fact that draping results in an increase in the fiber volume content (FVC). This increase originates from the compression of fibers along the curvature which is inversely proportional to the distance from the internal curvature radius along the through thickness direction. However, when the thickness is small, a uniform FVC of the draped zone can be assumed. In case of no inter-layer shifting, the ratio of the thickness is small, a uniform FVC of the draped zone can be derived by mapping the study), an approximation of the permeability drop in a draped zone can be derived by equation (1) and (2).

\[
\varphi = r_A \varphi_p - r_A + 1
\]

\[
A_d = \frac{A_p}{(R + h)^2 - R^2}
\]

where \( \varphi \) and \( \varphi_p \) are the porosities of the planar and draped preforms, \( A_d \) and \( A_p \) are the cross-sectional areas of a planar and the corresponding draped zone, \( L \) is the zone length, \( h \) is the part thickness, \( \theta \) is the curvature angle, and \( R \) is the internal curvature radius (Fig. 1). Based on the above, and given a known in-plane permeability vs. FVC relationship where the variable is the number of layers (derived by a typical in-plane permeameter study), an approximation of the permeability drop in a draped zone can be derived by mapping the \( \varphi \) with the corresponding

\[
K_i = \frac{\eta \rho}{6 \Delta \mu \nu} \left\{ \frac{2i_j}{R_j} - 3i_j^2 + R_i^2 \right\}
\]

where \( i \) is the in-plane axis (\( x \) or \( y \)), \( \varphi \) is the porosity, \( P \) is the injection pressure, \( i \) is the flow front along the \( i \)-axis, \( R_i \) is the inlet radius, and \( t_i \) is the time needed to achieve \( i \). Transforming equation (1) for the fluid movement between two points \( A \) and \( B \) along the \( i \)-axis where \( i_A > i_B \) yields equation (4).

\[
K_i = \frac{\eta \rho}{6 \Delta \mu \nu} \left\{ \frac{2i_j}{R_j} - 3(i_j^2 - i_B^2) \right\}
\]

where \( i_A \) and \( i_B \) are the flow fronts at points \( A \) and \( B \) and \( \Delta t_i \) the flow time between \( A \) and \( B \). Considering that a uniformly draped zone within a part can be modeled by an equivalent planar zone of different porosity given by equations (1) and (2), mutual division of equation (4) for a draped and an isodimensional planar zone which are being filled under the same conditions with the same fluid, yields an expression for the permeability of the draped zone (curvature) (equation (5)).

\[
K_{i,\mu} = \frac{\Delta t_{i,\mu}}{\Delta t_{i,\mu}} \left\{ \frac{2h i_j}{(R + h^2) - R^2} \right\} K_{i,\mu}
\]

where \( K_{i,\mu} \) and \( K_{i,\mu} \) are the draped and planar permeabilities along a planar axis, \( \Delta t_{i,\mu} \) and \( \Delta t_{i,\mu} \) the time of flow within the draped and planar zone. Besides the typical assumptions related to Darcy’s law, equation (5) is valid under the following additional restrictions:

- The draping zone can be modeled by an equivalent planar zone with porosity given by equation (1).
- The pressure drop from inlet to flow front of a uniformly draped preform remains the same as the one of the equivalent planar preform.
- The draping and planar zones have the same position relative to the inlet.
- The draping axis (Fig. 1b) is parallel to one of the planar axes (\( x \) or \( y \)).

Computational aspects

The correlation between flow time in the draped zone and permeability can alternatively be found by numerical optimization where the permeability is iteratively redefined such that the initial difference between theoretical approximation and measurements is minimized (Fig. 2). Minimization was achieved by Matlab function “fmincon” which is designed to find the minimum of constrained nonlinear multivariable functions. In this case, the function to be minimized was the Residual Sum of Squares modified for the flow time within two points (e.g. a draped zone) (equation (6)).

\[
\text{RSS}_{\text{diff}} = \sum_{j=1}^{N} \left( \Delta t_{j,\text{diff}} - \Delta t_{j,\text{pre}} \right)^2
\]
where \( N \) is the number of flow time measurements in a draped zone, \( j \) is the measurement index, \( \Delta t_{\text{me}} \) the measured flow time within a draped zone, and \( \Delta t_{\text{pre}} \) the predicted flow time (e.g. by simulations). The demand for numerical optimization for multiple simulation iterations each with different inputs can generally be satisfied by (a) modifying the simulation internal calculation algorithm or (b) by an artificial neural network (ANN) designed to reproduce certain simulation results. The second option was employed in this case, which carries the additional limitation of reproducing efficiently a narrow range of simulation results.

The operational window of the developed ANN is given in Table 1. The transfer function characterizing the particular ANN design is given in matrix form in equation (7).

\[
\Delta t_{\text{pre}} = f_2 \left( W_1 f_1 \left( W_2 K + B_1 \right) + B_2 \right)
\]

where \( f_1(x) = 1/(1 + e^{-x}) \) and \( f_2(x) = x \) (neural activation functions), \( W_1 \) and \( W_2 \) are the weights of the first and second layer, respectively, \( B_1 \) and \( B_2 \) the biases of the first and second layer, respectively, \( \Delta t_{\text{pre}} \) is the ANN prediction of the flow time between a given point couple (network output), and \( K \) the permeability (network input). Finally, based on the output of equation (7), the calculation and minimization of the RSS of difference between simulation and ANN outputs was allowed.

To validate the ANN, the flow time between two points for four point pairs (prediction output) as derived by both simulations and the ANN have been plotted (Fig. 4) against the in-plane permeabilities (prediction inputs). Moreover, the evolution of the error between simulation and ANN outputs throughout the training iterations (epochs) is presented in Fig. 5. Good agreement between the ANN and simulation outputs can be observed which proves that the ANN can recreate successfully the simulation results of any case within the limits defined in Table 1.
omega-shaped cavity was exploited, targeting specifically at the flow within the curvatures of the omega shape (Fig. 6). The development procedure for the specific tool including design aspects, deflection, heat transfer, and filling simulations was as well described in the past. The parameters characterizing the draping of the specific curvatures, as defined in equation (2), are:

\[ R = 25 \text{ mm}, \quad h = 3 \text{ mm}, \quad L = 22 \text{ mm}, \quad \theta = 45^\circ. \]

The tool supports heating by liquid that flows through heating channels opened in the tool body while it was designed to host different sensors, namely dielectric analyzer, direct current sensor, ultrasound sensor, and pressure transducers. All of the above detect (among other quantities) flow but technical

**Flow front detection**

As shown in the previous section, the in-plane permeability is a prerequisite for the identification of the draped permeability. For the identification of the in-plane permeability, an optical permeameter was used; a mold with a transparent top tool that allows visual observation of the flow front by camera. The principle of operation as well as the measurement procedure for the specific instrument was described in detail in the past in a study that exploited the optical permeameter to compare real world experiments with simulation results produced by different software packages. For the required measurements of flow time within a draped zone, an RTM tool with an omega-shaped cavity was exploited, targeting specifically at the flow within the curvatures of the omega shape (Fig. 6). The development procedure for the specific tool including design aspects, deflection, heat transfer, and filling simulations was as well described in the past. The parameters characterizing the draping of the specific curvatures, as defined in equation (2), are: \( R = 25 \text{ mm}, \quad h = 3 \text{ mm}, \quad L = 22 \text{ mm}, \quad \theta = 45^\circ. \) The tool supports heating by liquid that flows through heating channels opened in the tool body while it was designed to host different sensors, namely dielectric analyzer, direct current sensor, ultrasound sensor, and pressure transducers. All of the above detect (among other quantities) flow but technical
prevent contact with carbon (conductive) fibers, the tip can be electrically isolated with a thin glass wrap. A comparison of EMFS with the two most popular sensing techniques of in-plane permeameters is given in Table 2. Preliminary filling trials using (a) only the mold-mounted sensors and (b) both the mold-mounted sensors and the EMFS (placed at the mold-mounted sensor spots for comparability) showed that the wire itself when it has a diameter of 200–300 μm is not affecting flow in an observable way. Any observable influence to flow originated from the tip of the sensor which is bigger (~5 × 4 mm film electrode) and only when many tips were placed in a small area. Based on the above, to minimize possible flow disturbance by the EMFS, a wire of small diameter (200 μm) was chosen, small number of sensors were used (which is acceptable due to the focus only on curvatures and not the whole part), and the limitations allow their integration in the tool only on planar zones of the omega-shaped cavity. Up to eight vents placed on the parting line can be used as entry points for any type of material-embedded sensors, venting or both.

In this study, electrical microwire flow sensors (EMFS) that enter the RTM tool from existing vents and are fixed on the cavity surface, were employed to investigate flow on curvatures. Variations in the particular sensing technique have been used in the past for flow monitoring (e.g. SMARTweave™ or parallel electrodes⁴). Here, it was selected mainly due to its compatibility with curvatures (in contrast to optical detection or mold-mounted sensors). It is based on detecting the electrical resistance on the wire tip: when measuring a dry spot of the preform, the sensor indicates a very high value (open circuit) while a sudden drop in electrical resistance indicates matrix arrival. To prevent contact with carbon (conductive) fibers, the tip can be electrically isolated with a thin glass wrap. A comparison of EMFS with the two most popular sensing techniques of in-plane permeameters is given in Table 2. Preliminary filling trials using (a) only the mold-mounted sensors and (b) both the mold-mounted sensors and the EMFS (placed at the mold-mounted sensor spots for comparability) showed that the wire itself when it has a diameter of 200–300 μm is not affecting flow in an observable way. Any observable influence to flow originated from the tip of the sensor which is bigger (~5 × 4 mm film electrode) and only when many tips were placed in a small area. Based on the above, to minimize possible flow disturbance by the EMFS, a wire of small diameter (200 μm) was chosen, small number of sensors were used (which is acceptable due to the focus only on curvatures and not the whole part), and the

Figure 6  a the mold-mounted and material-embedded sensors with a glass film for electrical isolation, b the EMFS entering the tool by a vent, c the vents along the width of the cavity used only for venting, and d the produced omega-shaped part

| Table 2 Qualitative comparison of flow sensing techniques |
|-----------------------------------------------|
|                                      | EMFS         | Camera            | Tool-mounted sensors |
| Flow detection at Point/position error      | Points       | Full surface      | Points               |
| Number of flow positions monitored         | Varies/yes   | –                 | Fixed/No             |
| Fluid                                       | Any          | Oil               | Oil                  |
| Thermo-dynamical conditions (P, T)          | Any          | Room temperature | Room temperature, pressures ≤ 10 bar |
| Tool Investigated geometry                  | Any (entry by vents) | Special (transparent) | Special (integrated sensors) |
| Flow disturbance (can be acceptable in all cases) | Due to embedding sensors in material⁵ | Due to deflection of transparent tool⁶ | Due to intentional misalignment of sensors from the surface for electrical isolation⁷ |
| Manual labor                                | High         | Low               | Low                  |
| Implementation cost                         | Low          | Mid               | High                 |

In this study, electrical microwire flow sensors (EMFS) that enter the RTM tool from existing vents and are fixed on the cavity surface, were employed to investigate flow on curvatures. Variations in the particular sensing technique have been used in the past for flow monitoring (e.g. SMARTweave™ or parallel electrodes⁴). Here, it was selected mainly due to its compatibility with curvatures (in contrast to optical detection or mold-mounted sensors). It is based on detecting the electrical resistance on the wire tip: when measuring a dry spot of the preform, the sensor indicates a very high value (open circuit) while a sudden drop in electrical resistance indicates matrix arrival. To prevent contact with carbon (conductive) fibers, the tip can be electrically isolated with a thin glass wrap. A comparison of EMFS with the two most popular sensing techniques of in-plane permeameters is given in Table 2. Preliminary filling trials using (a) only the mold-mounted sensors and (b) both the mold-mounted sensors and the EMFS (placed at the mold-mounted sensor spots for comparability) showed that the wire itself when it has a diameter of 200–300 μm is not affecting flow in an observable way. Any observable influence to flow originated from the tip of the sensor which is bigger (~5 × 4 mm film electrode) and only when many tips were placed in a small area. Based on the above, to minimize possible flow disturbance by the EMFS, a wire of small diameter (200 μm) was chosen, small number of sensors were used (which is acceptable due to the focus only on curvatures and not the whole part), and the

| Table 2 Qualitative comparison of flow sensing techniques |
|-----------------------------------------------|
|                                      | EMFS         | Camera            | Tool-mounted sensors |
| Flow detection at Point/position error      | Points       | Full surface      | Points               |
| Number of flow positions monitored         | Varies/yes   | –                 | Fixed/No             |
| Fluid                                       | Any          | Oil               | Oil                  |
| Thermo-dynamical conditions (P, T)          | Any          | Room temperature | Room temperature, pressures ≤ 10 bar |
| Tool Investigated geometry                  | Any (entry by vents) | Special (transparent) | Special (integrated sensors) |
| Flow disturbance (can be acceptable in all cases) | Due to embedding sensors in material⁵ | Due to deflection of transparent tool⁶ | Due to intentional misalignment of sensors from the surface for electrical isolation⁷ |
| Manual labor                                | High         | Low               | Low                  |
| Implementation cost                         | Low          | Mid               | High                 |
achieve precise placement, the textiles were cut by a robotic
cutter, they were placed and draped manually layer-by-layer
on the bottom tool of the mold and the top tool of the mold
was moved by a pneumatic die holder at very low velocities
to prevent closing movements. Despite its poor drape, the
selected textile showed good conformability which allowed
the operator to place each layer into the curvature and spread
outwards (according to drape and conformability definitions
proposed in 22). A two-component polymeric matrix system
(MOMENTIVE Epikote RIMH 135/Epikure 1366) was injected
radially at five bars for all three preforms without vacuum
assistance. In total six vents (shown in Fig. 8) allowed efficient
air movement as the flow front progressed. Injection was only
initiated after preheating both the tool and matrix at 70 °C
which was maintained throughout the process. To detect the
flow time within these areas, EMFS were placed on the surface
of the preform. The tips were electrically isolated from the con-
ductive (carbon) preform by a thin glass film. The EMFS were
connected to a measurement unit (SYNTHESITES, OptiFlow)
that detects the electrical resistance and records the exact
arrival time. In total eight sensors were placed per filling exper-
iment, in pairs, such that the flow time along the draping is
measured in four different distances ($D$) from the
$y$-axis (Fig. 8).

The specific preforms were characterized by orthotropic
flow behavior which resulted in symmetry of the saturated
area among all four quadrants (ideally). This allowed one
measurement of the flow time at a different distance from
the $x$-axis (sensor pair) per quadrant (i.e. the same would
not be achieved in anisotropic flow) thus maximizing sensor pair
distances (sensor invasiveness minimization). Filling experi-
ments were repeated three times per preform for statistical
validity. The resulting flow times within the draped zone ($\Delta t_f$)
vs. $D$ are summarized in Fig. 9.

Permeability and flow time comparisons
Filling simulations (PAM-RTM) were executed with the aim
to identify the arrival time difference ($\Delta t_p$) between virtual
distances between the sensors were maximized (i.e. 90 cm
between sensor pairs, as discussed in Section Measurement
of flow time in the draped zone). Moreover, error in the sen-
or tip position (caused by manual placement or shifting by
the flow front) was taken into account by embedding the sensor on the surface. As such, precise measuring of the tip
final positions was possible and taken into consideration
in subsequent analysis and simulations.

Experimental procedure and results
In-plane permeability identification
Preforms made of the textile CYTEC Priform HTS40 (Woven
Carbon, 424 g/m², 6 K, 115 ± 5 warp yarns/m, 110 ± 10 weft
yarns/m) were investigated at the three in-plane FVCs
45.29, 52.91, and 54.63% (calculated using the expression
$FVC = (nξ/hρ) \times 100\%$ where $n$ is the layer number, $ξ$ the areal
weight, $h$ the cavity height, and $ρ$ the fiber density). Plant oil
was used to impregnate the preforms while radial filling took
place within an optical permeameter mold (transparent top
tool for observation by camera). The mold produces plates
of a variety of thicknesses which in this case were kept in the
range of 2–4 mm in order to avoid significant transverse flows.
To minimize deflection, a steel bar specifically formed to not
deter visibility was placed on the transparent tool. Three fill-
ing experiments were executed for each preform for statistical
validity. Appropriate code for flow front detection and per-
meability calculation according to equation (1), ran simulta-
neously with each filling experiment. The resulting in-plane
permeabilities vs. FVC are presented in Fig. 7.

Measurement of flow time in the draped zone
Three preforms of the same textile with the in-plane FVCs [%]:
47.64, 55.58, and 63.52 (preforms 1, 2, and 3, respectively)
were used this time in an actual RTM tool that produces 3 mm
thick omega-shaped parts. The variation in FVC results from
varying the layer number (6, 7, and 8 layers, respectively). To

Figure 7 The $K_x$ and $K_y$ permeabilities determined by the optical permeameter (points) and the corresponding fittings (lines). The errors are generated by the three filling repetitions per preform.
The conditions of validity of equation (5) are met while all parameters are now known, allowing the analytical calculation of the x-axis permeability in draped zones. As discussed in Section Theoretical background, equation (5) is applicable only when the flow times correspond to flow along the x-axis. In this case, $\Delta t_{x,\text{pp}}$ is measurable only along the x-axis therefore equation (5) can be used to calculate $K_x$ and not $K_y$. Moreover, for the same reason the calculation can be achieved only for the sensor pair 1.1 and 1.2.

On the contrary, by numerical optimization all sensor pairs are used while both $K_x$ and $K_y$ values can be derived. Figures 8 and 9 show the sensor positions and the flow time measurements along the draped zones of the omega-shaped RTM part vs. the measurement distance from the x-axis for the three preforms. The vertical errors are generated by the three filling repetitions per preform while the horizontal by placement errors.

Sensors placed in the actual sensor positions, using in-plane permeability values as inputs. The simulation was repeated for the three in-plane permeabilities that correspond to the FVC of the preforms in Section Measurement of flow time in the draped zone, as derived by the $\log(K_p) = F(\text{FVC})$ lines presented in Section In-plane permeability identification. Other simulation inputs were selected to be in agreement with the experiments of Section Measurement of flow time in the draped zone: temperature of 70 °C in tool and pre-heating, five bars of injection pressure, viscosity of 47 mPas that corresponds to 70 °C according to the datasheet of the matrix. As such, the conditions of validity of equation (5) are met while all parameters are now known, allowing the analytical calculation of the x-axis permeability in draped zones. As discussed in Section Theoretical background, equation (5) is applicable only when the flow times correspond to flow along the i-axis. In this case, $\Delta t_{x,\text{pp}}$ is measurable only along the x-axis therefore equation (5) can be used to calculate $K_x$ and not $K_y$. Moreover, for the same reason the calculation can be achieved only for the sensor pair 1.1 and 1.2.

On the contrary, by numerical optimization all sensor pairs are used while both $K_x$ and $K_y$ values can be derived. Figures
The simulations were executed for five cases (FVCs between 50 and 63%) after defining zones of different permeabilities (Fig. 12).

Discussion

A danger of this study was that any influence from draping could be within the permeability error, normally expected to be high due to preform structural uncertainties. The issue was minimized and for certain cases the influence of draping was isolated by (a) statistical experimentation (i.e. repeating the exact same experiment three times) which normalized scatter and (b) focusing on higher FVCs during the experimental determination of draped permeability (~47 to ~63%).
as compared to FVCs used in the in-plane permeability study (~45 to ~54%) which made the effect of draping more pronounced.

A clear tendency of the draped permeability derived by both interpretations of the experimental data \( \left( K_{d,cal} \right) \) and inverse approach \( \left( K_{d,opt} \right) \) towards lower values with FVC increase can be observed in Figs. 10 and 11. This permeability drop is within the error range at the first two preforms (draped FVCs: 50.38 and 58.78%) and significantly beyond error on the third preform (draped FVC: 67.18%). This behavior has been verified by both the analytical \( \left( K_{d,cal} \right) \) and inverse approach \( \left( K_{d,opt} \right) \). One plausible explanation is that nesting, which is significant at the high FVC, is related to a change in the \( \log(K) = F(FVC) \) slope (permeability drops more drastically). It is believed that the FVC of 67.18% may cause pronounced nesting resulting in a relatively lower permeability value that forces the slope of the tendency lines \( \log(K_{d,cal}) = F(FVC) \) and \( \log(K_{d,opt}) = F(FVC) \) to decrease compared to the \( \log(K_{d,cal}) = F(FVC) \). On the contrary, nesting in the theoretical approximation is not taken into account because it is based on measurements of ~4% lower FVC. The discussed difference in theoretically expected and experimentally derived permeability of a draped zone has an impact on the flow time within the draped zone. Figure 12 where the effect is quantified shows that the theoretical approximation of flow time per curvature presents an underestimation from reality; the underestimation degree is rising exponentially with FVC, reaching values above 30% for FVCs ~65%. As such, a practical potential of the methods in this study is to shorten the time disagreement observed between filling simulations and actual processes.

As can be observed in Fig. 8, there are two pairs of draped zones in the omega-shaped part: the pair closer and the pair further from the inlet. The final choice to investigate the pair further from the inlet was made for three reasons:

1. There, \( \Delta t \) is significantly higher and therefore lower measurement errors can be achieved.
2. The generally accepted solution of Darcy’s Law given in equation (3) carries a discrepancy: it approximates the elliptical inlet with a circular inlet which allows the model to converge to reality only when the flow front is significantly higher than the circular inlet radius.\(^{13}\) This hypothesis was verified in experiments where disagreement between filling simulations and actual flow in terms of time of flow advancement was only found close to the inlet.\(^{15}\)

3. Structural deformation of the preform (i.e. tow shifting) may take place if injection pressure is higher than the compaction pressure.\(^{3}\) Naturally, areas closer to the inlet where injection pressure is more significant are more probable to suffer from this deformation.

More limitations (often contradicting) were finally involved in the selection of the injection pressure: injection pressure has to be low enough to avoid significant preform deformation/sensor shifting phenomena, high enough to keep gravitational effects negligible/allow unproblematic injection even at high FVC and constant for all preforms (a validity condition of the developed ANN). Constant injection pressure of five bars was empirically found to minimize the above unwanted effects while it is a realistic value used in manufacturing (low-to-mid injection value for low pressure RTM).

**Conclusion**

The achievements of the current study that establish progress beyond the state-of-the-art in identifying the permeability of curvatures are summarized as follows:

- A permeability model that takes into consideration experimentally derived flow time within a draped zone has been developed to enable analytical calculation of the draped permeability. The limitations and assumptions of the model were identified and discussed.
- The numerical optimization concept used in the past was modified to focus only on draped zones and thus allowed the inverse calculation of draped permeability. Iterative flow time predictions (needed for optimization) which are not typically feasible with simulation software were achieved by an artificial neural network developed.
for this purpose. The network output was validated by a comparison with simulations, while the very narrow range of simulation results that the network is able to recreate is identified and discussed.

- A flow sensing technique compatible with measurements within curvatures of typical RTM tools was employed in actual RTM manufacturing of an omega-shaped part. The specific sensing technique was compared to other flow detecting techniques and its limitations were identified/discussed while the experimental plan was designed to be compatible with the conceptual work/limitations of all systems.

- The permeability of a certain curvature of actual fibrous preforms was finally derived both analytically and inversely based on the above methods and compared to theoretical expectations with respect to involved phenomena. The results of the experimentally determined permeability values for this curvature on filling simulations was investigated.

Acknowledgments

This work was supported by the Bundesministerium für Wissenschaft, Forschung und Wirtschaft and the FACC Operations GmbH.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCiD

Spirod Konstantopoulos http://orcid.org/0000-0002-2404-3182
Christian Hueber http://orcid.org/0000-0002-7598-8004
Ralf Schledjewski http://orcid.org/0000-0003-3121-6771

References

1. K. Han and L. J. Lee: ‘Dry Spot Formation and Changes in Liquid Composite Molding:– Experimental’, J. Compos. Mater., 1996, 30, (13), 1458–1474, DOI 10.1177/00219983960301303.
2. E. E. Swery, R. Meier, S. V. Lomov, K. Drechsler and P. Kelly: ‘Predicting permeability based on flow simulations and textile modelling techniques: Comparison with experimental values and verification of FlowTex solver using Ansys CFX’, J. Compos. Mater., 2016, 50, (5), 601–615, DOI 10.1177/0021998315579727.
3. N. Vernet, E. Ruiz, S. Advani, J. B. Alms, M. Aubert, M. Barburski, B. Barari, J. M. Beraud, C. Berg, N. Correa, M. Danz, T. Delavie, M. Dickert, C. Di Fritta, A. Endruweit, P. Ermanni, G. Francucci, J. A. Garcia, A. George, C. Hahn, F. Klinker, S. V. Lomov, A. Long, B. Louis, J. Maldonado, R. Meier, V. Michaud, H. Perrin, K. Pillai, E. Rodriguez, F. Trochu, S. Verheyden, M. Wietgrefe, W. Xiong, S. Zaremba and G. Ziegmann: ‘Experimental determination of the permeability of engineering textiles: Benchmark II’, Composites Part A, 2014, 61, 172–184, DOI 10.1016/j.compositesa.2014.02.010.
4. R. Arbter, J. M. Beraud, C. Binetruy, L. Bizet, J. Bréard, S. Comas-Cardona, C. Demaria, A. Endruweit, P. Ermanni, F. Gommer, S. Hasanovic, P. Henrat, F. Klinker, B. Laine, S. Lavanchy, S. V. Lomov, A. Long, V. Michaud, G. Morren, E. Ruiz, H. Sol, F. Trochu, B. Verleye, M. Wietgrefe, W. Wu and G. Ziegmann: ‘Experimental determination of the permeability of textiles: A benchmark exercise’, Composites Part A, 2011, 42, (9), 1157–1168, DOI 10.1016/j.compositesa.2011.04.021.
5. S. Konstantopoulos, H. Grossing, P. Hergan, M. Weninger and R. Schledjewski: ‘Determination of the unsaturated through-thickness permeability of fibrous preforms based on flow front detection by ultrasound’, Polym. Compos., 2016, in press, DOI 10.1002/poc.23944.
6. B. R. Gebart and P. Lidström: ‘Measurement of in-plane permeability of anisotropic fibre reinforcements’, Polym. Compos., 1996, 17, (1), 43–51, DOI 10.1002/pc.10589.
7. H. Groessing, D. Becker, S. Kaufmann, R. Schledjewski and P. Mitschang: ‘An evaluation of the reproducibility of capacitive sensor based in-plane permeability measurements: A benchmarking study’, eXPress Polym. Lett., 2014, 9, (2), 129–142, DOI 10.3144/expresspolymlett.2015.14.
8. K. Okonkwo, P. Simaček, S. G. Advani and R. S. Parnas: ‘Characterization of 3D fiber preform permeability tensor in radial flow using an inverse algorithm based on sensors and simulation’, Composites Part A, 2011, 42, (10), 1283–1292, DOI 10.1016/j.compositesa.2011.05.010.
9. G. Morren, S. Bossuyt and H. Sol: ‘2D permeability tensor identification of fibrous reinforcements for RTM using an inverse method’, Composites Part A, 2008, 39, (9), 1530–1536, DOI 10.1016/j.compositesa.2008.05.019.
10. S. Bickerton, E. M. Sozer, P. Simaček and S. G. Advani: ‘Fabric structure and mold curvature effects on preform permeability and mold filling in the RTM process. Part II. Predictions and comparisons with experiments’, Composites Part A, 2000, 31, (5), 439–458, DOI 10.1016/S1359-835X(99)00088-3.
11. S. Bickerton, E. Sozer, P. Graham and S. Advani: ‘Fabric structure and mold curvature effects on preform permeability and mold filling in the RTM process. Part I. Experiments’, Composites Part A, 2000, 31, (5), 423–438, DOI 10.1016/S1359-835X(99)00087-1.
12. J. R. Weitenböck, R. A. Shenoi and P. A. Wilson: ‘Measurement of three-dimensional permeability’, Composites Part A, 1998, 28, (1–2), 159–169, DOI 10.1016/S1359-835X(97)00049-3.
13. J. R. Weitenböck, R. A. Shenoi and P. A. Wilson: ‘Radial flow permeability measurement Part A: Theory’, Composites Part A, 1999, 30, (6), 781–796, DOI 10.1016/S1359-835X(98)00183-3.
14. M. T. Hagan, B. D. Ehmler and M. H. Beale: ‘Neural network design’, 1st edn; 1996, Boston, MA, PWS Pub.
15. H. Grossing, N. Stadlmajer, E. Fauster, M. Fleischmann and R. Schledjewski: ‘Flow front advancement during composite processing: Predictions from numerical filling simulation tools in comparison with real-world experiments’, Polym. Compos., 2013, 37, 2782–2793, DOI 10.1002/pc.23474.
16. H. Grossing, S. Konstantopoulos and R. Schledjewski: ‘Numerical Filling Predictions and Mechanical Mold Simulations for Composite Manufacturing Techniques: RTM Tool Development’, KEM, 2015, 651–653, 423–432, DOI 10.4028/www.scientific.net/KEM.651-653.423.
17. S. Konstantopoulos, E. Fauster and R. Schledjewski: ‘Monitoring the production of FRP composites: A review of in-line sensing methods’, eXpress Polym. Lett., 2014, 8, (11), 823–840, DOI 10.3144/expresspolymlett.2014.84.
18. B. K. Fink, R. C. Don and J. W. Gillespie: ‘Development of a Distributed Direct Current Sensor System for Intelligent Resin Transfer Molding’, Army Research Laboratory, Aberdeen Proving Ground, MD, 1999.
19. T. Luthy and P. Ermanii: ‘Linear direct current sensing system for flow monitoring in Liquid Composite Moulding’, Composites Part A, 2002, 33, (3), 385–397, DOI 10.1016/S1359-835X(01)00115-4.
20. J. S. Sirkis and A. Dasgupta: ‘The Role of Local Interaction Mechanics in Fiber Optic Smart Structures’, J. Intell. Mater. Syst. Struct., 1993, 4, (2), 260–271, DOI 10.1177/1045389X930040216.
21. G. Liu, R. S. Parnas and H. S. Giffard: ‘New set up for in-plane permeability measurement’, Composites Part A, 2007, 38, (3), 954–962, DOI 10.1016/j.compositesa.2006.06.024.
22. J. Summerscales and S. Grove: ‘Manufacturing methods for natural fibre composites’, in ‘Natural fibre composites: materials, processes and properties’, (ed. A. Hodzic and R. Shanks), 176–215; 2014, Oxford, Woodhead Publishing.