Metrological determination of inhomogeneous hydrodynamic compaction during unsaturated out-of-plane permeability measurement of technical textiles

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ABSTRACT
An out-of-plane permeability measurement system is presented that initially enables monitoring of inhomogeneous hydrodynamic compaction of textiles during impregnation. For this, it provides linear variable differential transformers (LVDTs) in combination with ultrasonic technology, allowing continuous tracking of total stack compaction, flow front progression and single layer displacement. From this data the non-linear distribution of fiber volume content ($V_f$) along with the sample thickness can be derived. Hence, data required for the validation of corresponding numerical models is generated, which again allows accounting measured permeability to a certain $V_f$. It can also be used for parameter studies regarding the influence of process- and material-related parameters on the processing behavior of technical textiles during liquid composite molding processes.

GRAPHICAL ABSTRACT

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Introduction
Liquid composite molding (LCM) processes, in which thermoset resin impregnates a dry typically textile-based reinforcement structure, are widely used for industrial manufacturing of fiber reinforced polymer composites. For shell-like parts, i.e. with a large surface area in relation to thickness, out-of-plane impregnation can significantly reduce cycle times due to flow path length reduction. To optimize LCM processes, knowledge about textile permeability is crucial. Permeability describes conductance of a porous media for fluid flow and is defined by Darcy’s law (Equation 1) for saturated flow [1]:

$$\vec{v} = -\frac{K}{\eta} \nabla p$$

Here $\vec{v}$ is the volume-averaged fluid velocity, $\nabla p$ is the pressure gradient, $\eta$ is the viscosity of the fluid and $K$ is the permeability tensor of the porous media. The equation can also be used for the
unsaturated case, when flow front position $L(t)$, pressure gradient $\nabla p(t)$ and the volume flow $Q(t)$ (all depending on time) are known, furthermore the sample area $A$ is also needed. For a three-dimensional case, $K$ is defined by a second order tensor, which is often reduced for textiles:

- $K_1$ highest in-plane permeability
- $K_2$ lowest in-plane permeability
- $K_3$ out-of-plane permeability

Experimental determination of permeability is commonly done by impregnation (unsaturated flow) under controlled conditions regarding injection pressure or flow rate, while using a fluid with a known viscosity. Flow front tracking allows deriving $\bar{V}$ and Darcy’s law is then applied to calculate permeability. $V_F$ strongly impacts permeability and therefore experiments are usually performed at specific levels of $V_F$. However, fluid flow can lead to textile deformation causing undefined deviations from the intended $V_F$. This is a challenge especially for transverse permeability measurements, where the complete stack undergoes a complex hydrodynamic compaction, illustrated in Figure 1.

Initially, when fluid flows into the cavity, in which the textile stack is placed, the stack will be homogeneously compacted by fluid pressure. Simultaneously, the impregnation begins. During the impregnation process there is a non-linear pressure gradient between fluid entering and flow front, which can be approximated by a combination of Darcy’s law (Equation 1) with Terzaghi’s principle (Equation 2) [2, 3]. The latter defines that for each infinitesimal element of the textile stack, effective compaction pressure acting on the textile $p_{\text{eff}}$ is given by total pressure $p_{\text{total}}$ in pure fluid zone over the stack ($= injection pressure$), subtracted by fluid pressure $p_{\text{fluid}}$ at the position of the layer.

$$p_{\text{total}} = p_{\text{eff}} + p_{\text{fluid}}$$  \hspace{1cm} (2)

Pressure drops over the flow length due to the flow resistance of the textile and hence, compaction pressure increases to its maximum at the flow front and is constant in the dry preform area. Accordingly, $V_F$ increases between fluid entry and flow front. This has been shown in experimental and simulative investigations e.g. by Klunker et al. [4]. Transverse permeability is decreasing with increasing $V_F$ (quasi-exponential correlation) [4]. This in turn affects fluid pressure evolvement which again affects $V_F$ etc., there is a loop of interdependency between $V_F$ and permeability. The time delay of compaction behavior of the preform is mainly caused by a viscous compaction response, which leads to this loop. The objective of the development leading to the new measurement system was not bypassing these effects during measurement, as this is never fully possible and to enable monitoring all of these effects under well-defined process conditions, as they occur in real-life processes.

**Experimental set-up**

Figure 2 shows a photograph, CAD-model and schematic illustration of the novel measurement system that is supposed to fulfill the following requirements:

- Generation of an unsaturated flow at constant injection pressure up to 10 bar
- Defined initial $V_F$ (cavity height)
- Continuous metrological determination of:
  - Pressure drop
  - Flow rate
  - Flow front progression
  - Total stack compaction (change of thickness of sample)
  - Single layer movement (reference layer for validation of $V_F$ distribution) under saturated condition

As can be seen in Figure 2, the sample is positioned between two perforated aluminum discs which act as distribution media. A pressure vessel feeds the system with fluid and the flow rate is measured with a flow meter. The resulting actual pressure drop is monitored by pressure transducers positioned before the lower distribution media and the above upper distribution media. Ultrasonic technology (through-transmission method) is used for continuous flow front monitoring. This approach, initially developed by Stöven et al. [5], exploits the difference in speed of sound in dry and wet regions, leading to a decrease of time of flight with progressing flow front. While the upper distribution media
is fixed, the lower one is moveable and in permanent contact with the spring-loaded linear LVDTs. When hydrodynamic compaction occurs and the total stack is getting compacted (change of thickness of the sample), the lower distribution media will follow this movement. For monitoring of single layer
displacement, ultrasonic technology following impulse-echo method is applied. In this case, a single ultrasonic head is used as transmitter and receiver. A small metallic insert (aluminum foil, Ø 10 mm and a thickness of 0.025 mm) is placed between two layers, within the stack, and acts as hard reflecting material for ultrasound. By applying different injection pressures, the movement of the insert can then be tracked. With the knowledge of the total compaction and the insert displacement, \( V_F \) distribution in flow-through area can be approximated.

The results of the validation tests are shown in Figure 3. To validate the accuracy of the impulse-echo method for single layer displacement, a validation test was performed in which the movement of the lower distribution media is simultaneously tracked with LVDTs and ultrasonic (Figure 3, Diagram (1)). The results of the ultrasonic measurements are within the standard deviation of the three LVDTs.

The second validation test (Figure 3, Diagram (2)) compares ultrasonic flow front monitoring with a theoretical calculation based on the flow meter results. For this, the flow front progression \( L(t) \) is approximated based on injected volume over time \( V(t) \), the total \( V_F \) and area of the sample \( A \) are needed (only valid if hydrodynamic compaction is negligible and \( V_F \) is fairly constant over thickness):

\[
L(t) = \frac{V(t)}{A*(1 - V_F)}
\] (3)

The characteristics of progresses show good agreement up to the point where hydrodynamic compaction becomes significant and causes a fluid rich zone in the lower area.

The third validation test focused on monitoring total compaction and movement of an insert placed in the middle of the stack behind ply 15, depending on step-wise pressure increase (Figure 3, Diagram (3)a). Figure 3, Diagram (3)b shows the movements relative to the initial position at 0 bar. If compaction was homogenous, the movement of the first layer (LVDTs) should be twice as high as the movement of the middle layer (insert). As this is not the case, it proves inhomogeneous compaction resulting from relaxation at the first layers (in flow direction) and maximum compaction at the last layers. Furthermore, the single layer displacement shows a time-depending reaction behavior. Yet, for an exact textile behavior determination, further investigations with different textiles, \( V_F \), pressure steps and amounts of layers must be carried out.

**Conclusion**

The novel measurement system allows simultaneous tracking of the flow front progression and the total compaction during impregnation, as well as simultaneous single layer displacement and total compaction monitoring depending on injection pressure under saturated conditions. Validation tests prove the functionality, so it can be used for parameter studies with the objective to gain insights about the influence of process- and material-related parameters on the processing behavior of technical textiles during LCM.

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No potential conflict of interest was reported by the authors.

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