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RTM & PERMEABILITY

Location
MED 3 1119

1. Goals

In this TP, we will show why the concept of permeability plays an important role in impregnation for liquid composite molding processes (LCM), and how it can be measured. Using a simplified setup for RTM (Resin Transfer Molding), which is a particular case of LCM, we will discuss the links between the resin velocity v and the permeability K of reinforcements.

Our goal here is to measure the longitudinal permeability of a compressed stack of fabric. Since we are solely interested in impregnation, we will use silicon oil as a test liquid, which will not solidify in this experiment. The permeability will be assessed in two-phase *("unsaturated")* and in single-phase *("saturated")* flow configurations from a 2-steps experiment, following the guidelines in the annexes:

- Emulate and monitor the impregnation step in a RTM process
- Prepare the fabric and the experimental setup
- Record the evolution of the flow front position
- Measure the liquid flow rate when it is fully saturated
- Analyze the results and determine the 1D longitudinal permeability of the fabric
- Compare the permeability K_{unsat} measured in the *unsaturated* configuration (two-phase flow) and K_{sat} measured in the *saturated* configuration (single-phase flow).

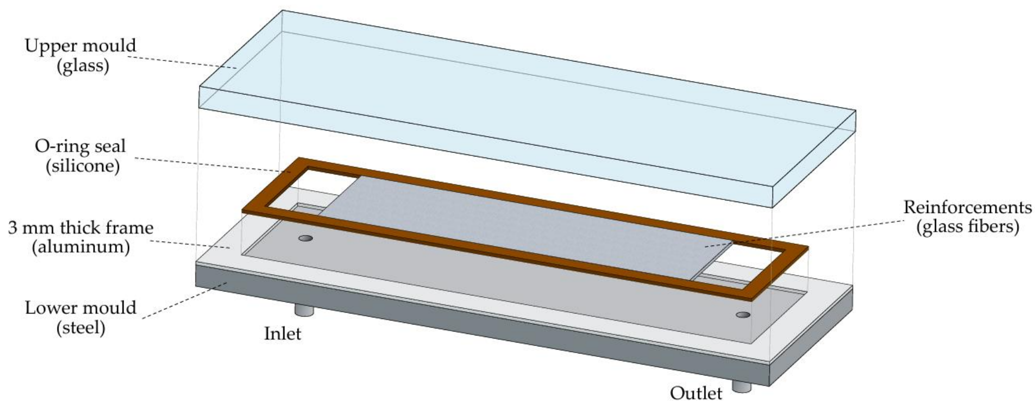

Figure 1: Schematic of the mould setup

2. Experimental procedure

2.1. Fabric and mould preparation

- Open and clean the mould. Make sure markings are still present.
- Calculate the number n of fabric layers needed to get $V_f = n\sigma/(\rho h) = (35\pm3)\%$ — with the thickness h of the mould frame and the fabric properties ρ, σ given in Table 1.
- Cut the fabric into n rectangles of 350 mm×100^{+1}_{-0}mm.
  Check that they fit the mould perfectly: there should be no empty space on the sides.
- Weigh the fabric stack to determine the precise fiber volume fraction $V_f = m_f/V_{mold}$.
- Place the metallic frame , the silicon O-ring seal and the fabric according to Figure 1.
- Close the mould, place the pins and apply a pressure of ~ 3.5 bar to compress the fibers.
- Prepare the pressure pot (check that there is enough liquid left). With the valve closed, apply a pressure of approximately 700 mbar (70 kPa).
- Place the camera, set its focus on the fabric.
- Ensure that the mass and pressure acquisition program runs without errors.

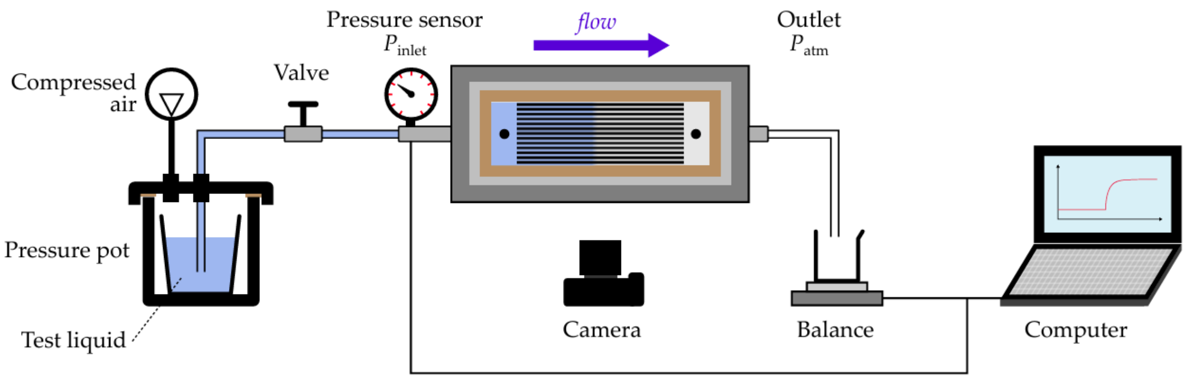

Figure 2: Schematic of the permeability measurement setup

2.2. Injection of the test fluid

- Start the video (camera).
- Start the pressure and mass acquisition (PC).
- Open the valve.
- Let the camera record the flow front position $x(t)$ during impregnation (unsaturated/two-phase flow) and then stop the video.
- Let the mass program record ~ 1 minute of outcoming fluid.

3. Data analysis

The experimental data produced during the TP includes the video of the flow front, the recording of pressure ΔP (t), and the mass of liquid flowing out $m(t)$ recorded by the balance.

3.1. Unsaturated permeability

The resin filtration process is considered as flow of a Newtonian fluid in a porous medium, which is driven by a pressure gradient throughout the porous medium itself. In combination with the mass conservation equation, Darcy's law is commonly used in LCM to describe this type of flow. For isothermal saturated flow in a rigid preform it takes the following expression:

$$\nu = -\frac{K}{\eta(1 - V_f)} \nabla P \tag{1}$$

Where ν is the fluid velocity, η the fluid viscosity, V_f the volume fraction of fibers, ∇P the pressure gradient, and K is fabric permeability. For one-dimensional flow of an incompressible fluid under constant applied pressure at the mold inlet, assuming a slug-flow boundary condition at the flow front and neglecting capillary pressure drop at the flow front, pressure is found to decrease linearly along the impregnated portion of the fabric, i.e. between the mold inlet (P_i) and the flow front (P_f) (Fig. 3).

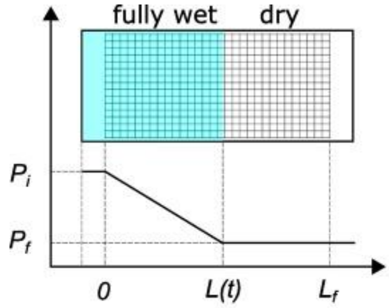

Figure 3: Schema of impregnation showing the pressure profile along the fabric stack

Therefore, at any moment during the impregnation, the pressure gradient can be expressed as

$$\nabla P = \frac{P_f - P_i}{L(t)} = \frac{\Delta P}{L(t)} < 0 \tag{2}$$

Where $L(t)$ is the flow front position at time t. Pressure at the flow front is assumed to be the pressure of the air in the dry fabric (typically atmospheric pressure). Thus, Eq. (1) becomes

$$\frac{dL(t)}{dt} = -\frac{K}{\eta(1 - V_f)} \frac{\Delta P}{L(t)} \tag{3}$$

Which after integration leads to

$$L^2(t) = -\frac{-2K_{unsat}}{\eta(1 - V_f)} \Delta P\ t \tag{4}$$

From Eq. (4) follows that a measurement of the flow front position as a function of time, under constant-pressure impregnation allows an indirect measurement of permeability. In this case, it is referred to as unsaturated permeability, denoted as K_{unsat}.

How to use Eq. (4) for K_{unsat} measurement

- Plot the evolution of the square of the flow front position $x^2(t)$ and find its slope (like figure 4).

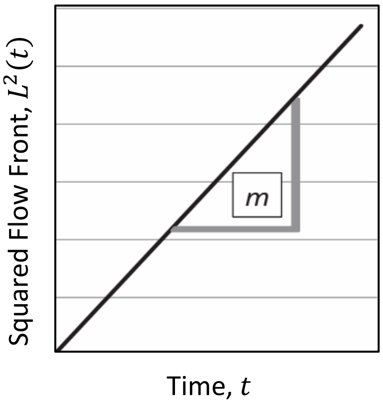

Figure 4 Schematic graph of typical constant pressure ow front position squared versus time results.

- Determine the average pressure difference ΔP between the outlet and the inlet.
- Deduce the permeability K_{unsat}

3.2. Saturated permeability

In saturated unidirectional measurements, the permeability is calculated directly from

$$\frac{Q_{out}}{A} = -\frac{K_{sat}}{\eta}\frac{\Delta P}{L} \tag{5}$$

- Plot m(t) and its slope $\frac{dm}{dt}$. Deduce the average volumetric flow rate $Q = \frac{dv}{dt}$
- Calculate the corresponding permeability K_{sat}.

For more information read annex III and II.

4. Report

Write a short report of the whole TP **(maximum 10 pages)** in English. Make sure to report all measurements, significant figures and calculations. Plot the data when it is relevant and pay attention to the plot layouts. The following items should be included in the report, following the order that suits you the best while remaining logical:

- *Short* general introduction on the context of LCM (principles, applications, issues, etc.).
- Context on permeability (why is it important for LCM, definition, equations, etc.). **Exercise:** deduce the theoretical liquid velocity $v(t)$ in unidirectional flow at constant applied pressure by integrating Darcy's law (Equation 1):
- Explain what was done in this TP: (goal, motivation, methods)
- Results and analysis:
  - Compare the theoretical flow front velocity $v(t)$ with your measurements.
  - Compare the two methods for measuring permeability.
  - Calculate the ratio $R = K_{\text{unsat}}/K_{\text{sat}}$ and discuss its value (why?).
- Write a short conclusion.

The main point of the report is to evaluate your ability to be concise and clear and to show that you understood the subject, the experiment and how they relate to each other.

Parameters & values

Some of the parameters needed in order to calculate K are summed up in Table 1. The areal density of fabrics σ (also known as gsm) might differ slightly in the experiments. The fabric used during the TP is flax fabric.

Table 1 Experimental parameters

h_{mould} [mm]	η [Pa · s]	ρ_{liq} [kg/m^3]	ρ_{flax} [kg/m^3]	σ_{flax} [g/m^2]
3	0.1	965	1450	300

With h_{mould} the thickness of the mould, η the silicone oil viscosity at 25°C, ρ the density and σ the areal density.