Composite forming
2021-2022

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Outline

I. General points

II. Constituents of composites (Matrix, Reinforcement)

III. Composites forming processes

IV. Common issues on processes

V. Resin Transfer Molding (RTM) process

VI. The law of Darcy

VII. Heat transfer during curing

VIII. Heat transfer in the mold

I. General points

- **Definition: Assembly of two or more materials that provides higher properties to the final material than the properties of each initial components.**

- **We called "composites" arrangements of reinforcements embedded in a matrix whose mechanical strength is much lower. The matrix ensures cohesion and maintains the orientation of the fibers, it also transmits the stresses to which the parts are subjected. These materials are very heterogeneous and anisotropic.**

Main Composite Materials

Cob:
Soil+straw

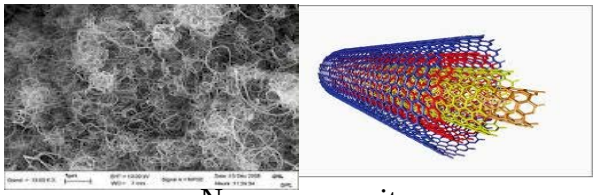
Organic matrix composites

Metal Matrix Composites

Reinforced concrete

Ceramic Matrix Composites

Bio-composites



Nano-composites

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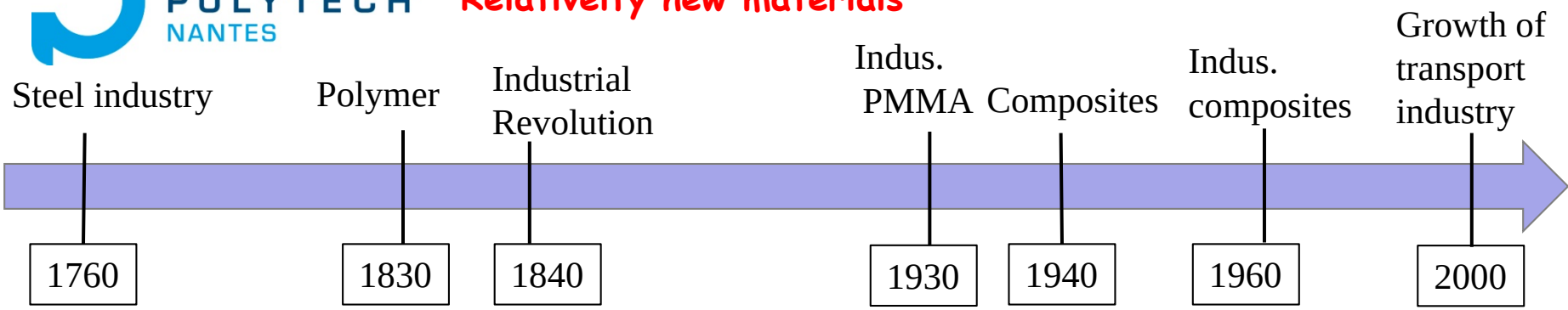
Relativelty new materials



Light and resistant materials

Tableau 1 – Comparaison de caractéristiques de matériaux composites et de métaux (d'après A. NÉGRIER et J.C. RIGAL)

Caractéristiques	Métaux			Composites à matrices organiques (1)					Composites à matrice métallique (1)
	Acier 35 NCD 16	Alliage aluminium AU 4 SG	Alliage titane TA 6 V	Bore/ résine époxyde	Carbone HR/ résine époxyde	Carbone HM/ résine époxyde	Aramide/ résine époxyde	Verre R/ résine époxyde	Bore/ aluminium
Caractéristiques en traction :									
Résistance à la rupture R .... (MPa)	1 850	500	1 000	2 000	1 000 à 1 300	1 000	1 300 à 1 800	1 800 à 2 000	1 250 à 1 800
Module d'Young E ..... (GPa)	200	72	110	220	130	200	75	53	230
Masse volumique ρ ..... (g/cm^3)	7,9	2,8	4,45	2,1	1,5	1,7	1,37	2	2,7
Résistance à la rupture massique $R/\rho g$ ..... (km)	24	18	23	95	65 à 85	60	95 à 130	90 à 100	45 à 65
Module d'Young massique $E/\rho g$ .....(km)	2 500	2 600	2 500	10 500	8 700	11 800	5 500	2 650	8 500

High specific mechanical properties

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Interest of composite materials

Applications in all industries for which **mass reduction** represent a strategic issue

Assembly: gluing, welding, preparation of semi-finished products can be easier than conventional materials...

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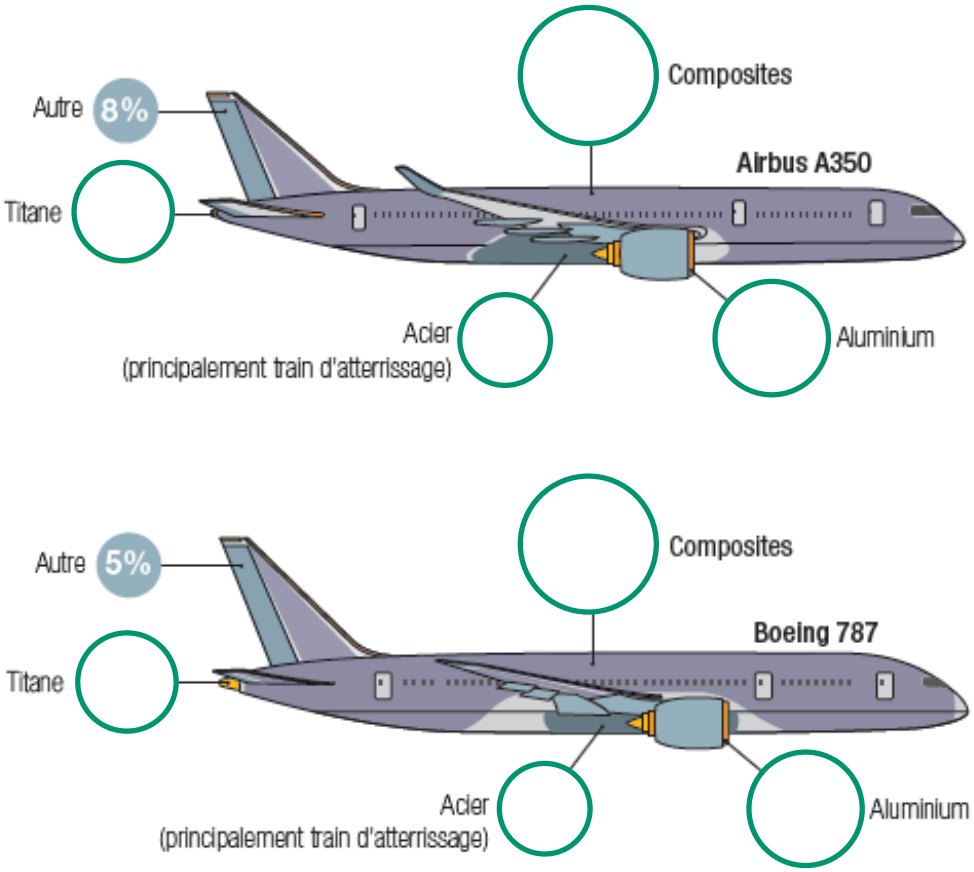

Mass proportions?

II. Constituents of composites

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Matrix

2 major classes of organic polymers:

- Thermosetting polymers
- Thermoplastic polymers

Reinforcement

Classified by:

- Material type: glass, carbon, aramid, flax
- Structure: mat, UD, fabrics

Thermoplastics: The phase change is physical and corresponds to a transition between a solid and a melted state. This transition is **reversible → recycling**

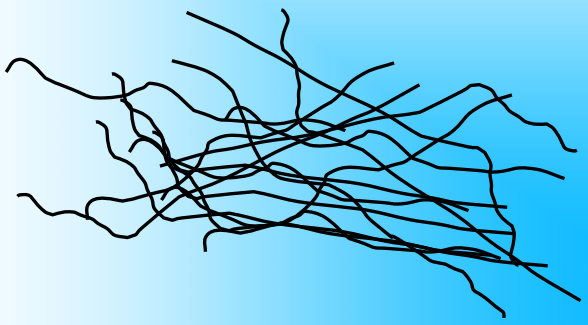
Issues for the composite forming: These materials are **VERY VISCOUS** (~1000Pa.s)

2 types of thermoplastic polymers

Amorphous polymers

No orientation of macromolecular chains

Ex: ABS



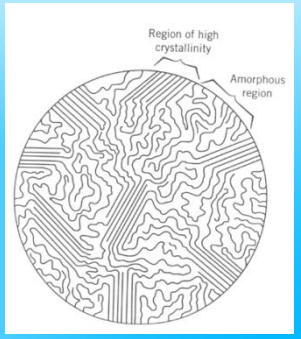
Semi-crystalline polymers

Orientation of a portion of the chains

Ex: PA, PEEK

→ Higher mechanical properties than amorphous

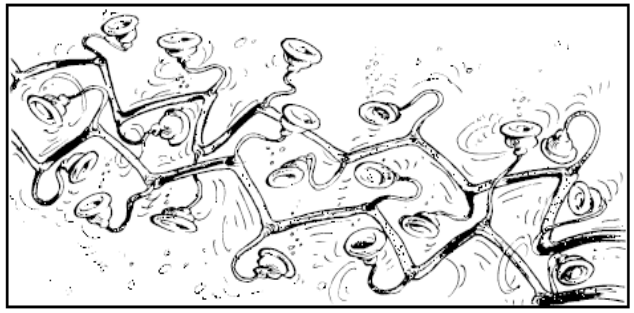
→ Exothermic crystallization + shrinkage



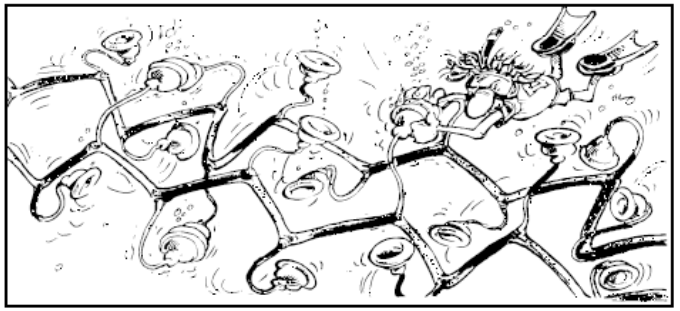
Thermosettings: The solidification occurs by binding of the macromolecules through one or several thermally activated chemical reactions. This chemical reaction is often called **crosslinking** because a 3D network is created within the material. This reaction is **irreversible**

Low viscosity material (about 0.1 to 10Pa.s)→low pressures (several bars) are required for the forming

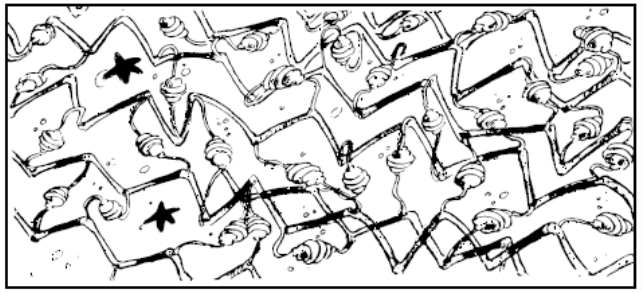
Pre-polymers (with free reactive sites)



Cure (joining of reactive sites)



Cured polymer



We called α the conversion degree:

→ α=0 : non crosslinked

→ α=1 : fully crosslinked

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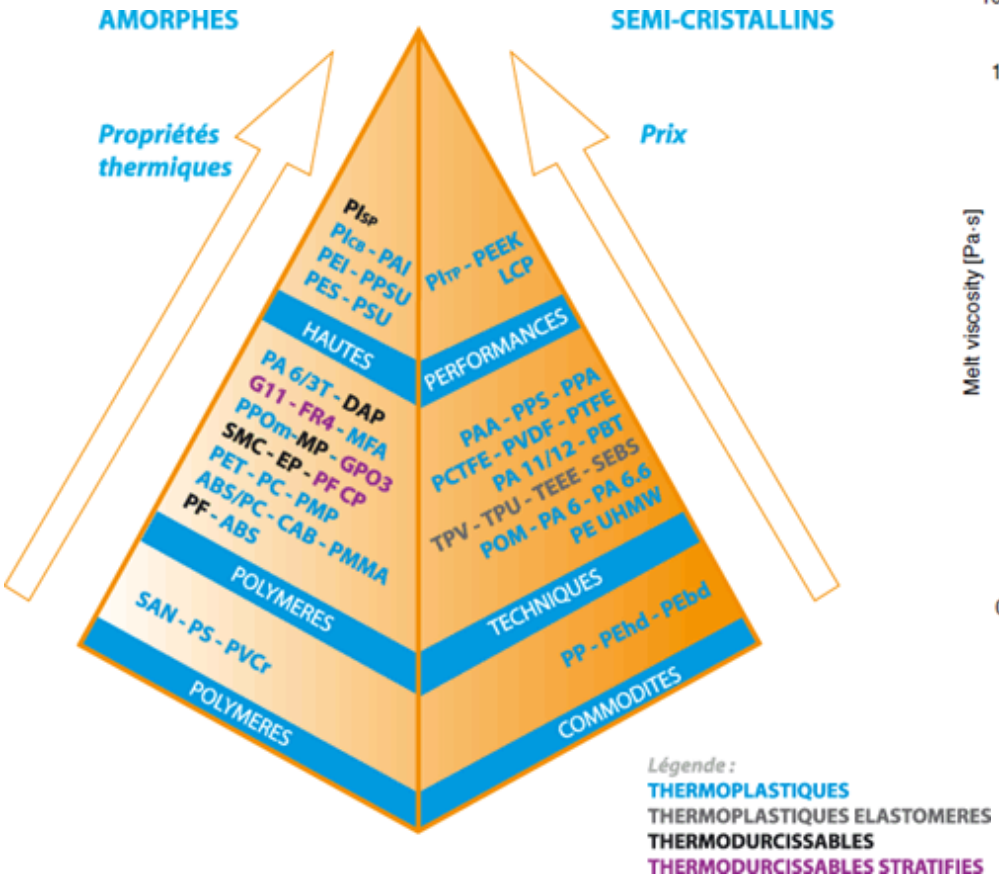
Thermosetting resins

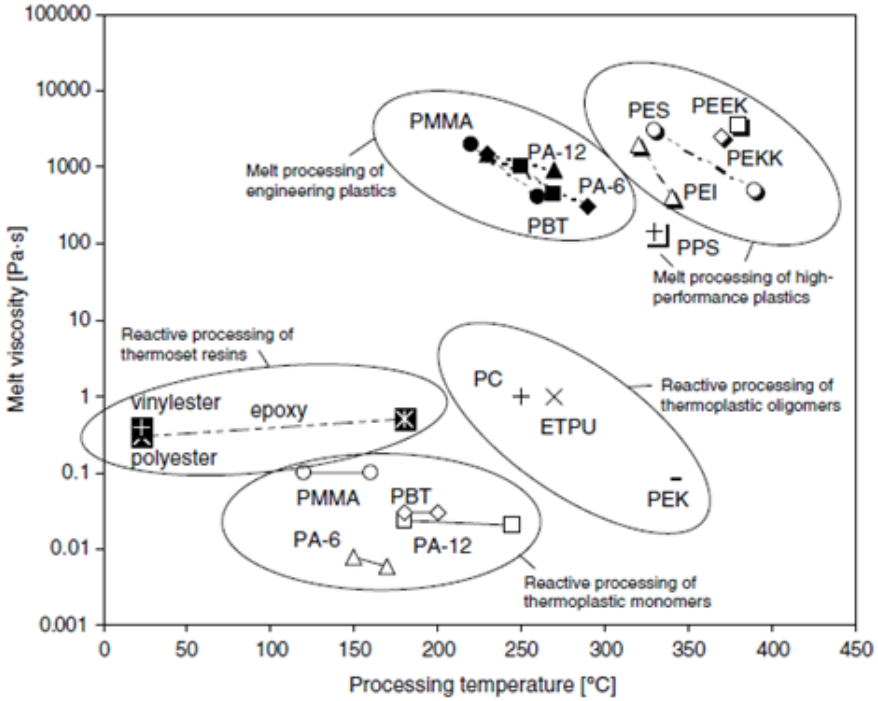
Type	Advantages	Drawbacks
Polyester	o Good adhesion on glass oGood chemical resistance oEasy processing oTemperature stability (> 150 ° C) oPrice	o Inflammability o Shrinkage o Limited pot life o Emission of styrene
Epoxy	oMechanical strength,thermal, chemical and fatigue o Excellent adhesion to fiber oEasy processing	o high price o Sensitivity to moisture and UV o Sensitivity to mechanical impact o Cure Time
Vinylester	o Good Fatigue behavior oExcellent corrosion behavior	o Combustible
Phenolic	o Good fire resistance	oFragile, sensitive to moisture o Difficult to process
Polyurethane	o Ease of molding o chemical resistance o aging	Strucutural strengh o combustibility o difficult to color
Polyimide	o Temperature stability (>250°C)	o Difficult to process o Very expensive

Mechanical properties

Thermoset polymers	Density (kg/m^3)	Longitudinal Young's modulus (Mpa)	Shear modulus (Mpa)	Poisson Coefficient	Stress at break (Mpa)	Elongation at break (%)	Coefficient of Thermal Expansion CTE (1/K)
Epoxyde	1 200	4 500	1 600	0,4	130	2	1,10E-04
Phénolique	1 300	3 000	1 100	0,4	70	2,5	1,00E-05
Polyester	1 200	4 000	1 400	0,4	80	2,5	8,00E-05
Uréthanne	1 100	700 à 7 000	?	?	30	100	?
Vinylester	1 150	3 300	?	?	75	4	5,00E-05
Polyimide	1 400	4 000 à 19 000	1 100	0,35	70	1	8,00E-05

Classification of polymers





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Glass fibers

The most used type.
There are 3 types:
- E : for composites mass market and common applications ;
- R : for high performance composites;
- D : For the manufacture of printed circuit boards (dielectric properties).

Aramid fibers

Often called KEVLAR ®. It is possible to find two types of aramid fibers of different stiffness:

- Low modulus fibers: used for cables and bulletproof vests ;
- High modulus fibers : used in high performance composites.

Carbon fibers

The most commonly used type for high performance applications.
There are two types of

- High strength fibers (HR) : combustion from 1000 to 1500 °C ;
- High modulus fibers (HM) : combustion from 1800 to 2000 °C.

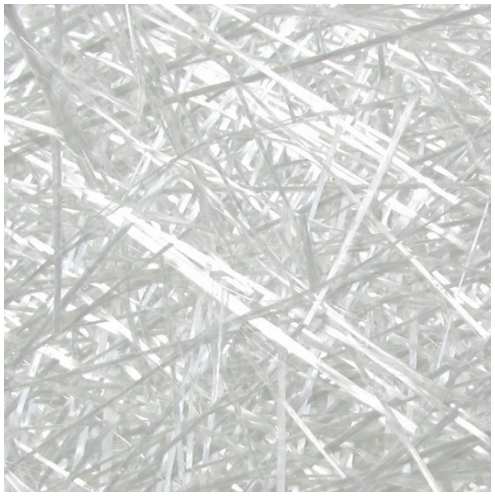
Flax fibers

Natural material

Mechanical properties

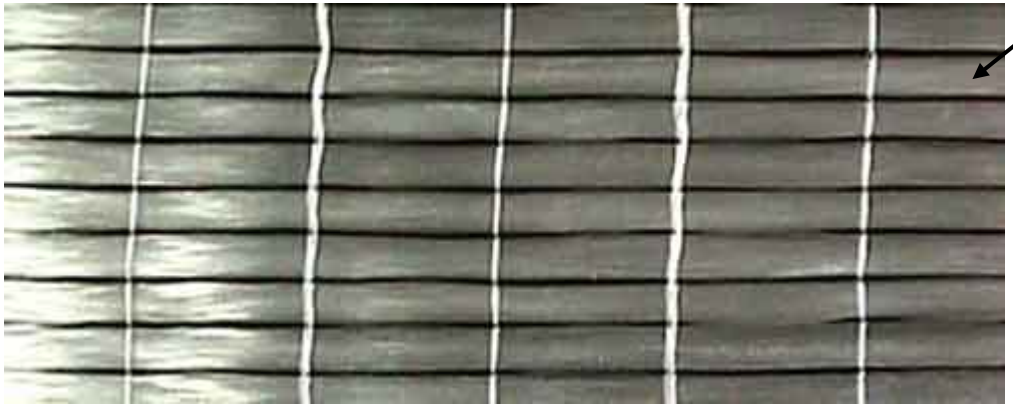
Reinforcement	Filament diameter (µm)	Density (kg/m³)	Longitudinal Young's modulus (Mpa)	Shear modulus (Mpa)	Poisson Coefficient	Stress at break (Mpa)	Elongation at break (%)	Coefficient of Thermal Expansion CTE (1/K)
Verre E	16	2600	74 000	30 000	0,25	2 500	3,5	5,00E-06
Verre R	10	2500	86 000		0,2	3 200	4	3,00E-06
Carbone HM	6,5	1800	390 000	20 000	0,35	2 500	0,6	8,00E-07
Carbone HR	7	1750	230 000	50 000	0,3	3 200	1,3	2,00E-07
Kevlar 49	12	1450	130 000	12 000	0,4	2 900	2,3	-2,00E-06

Structure of reinforcement: the mat

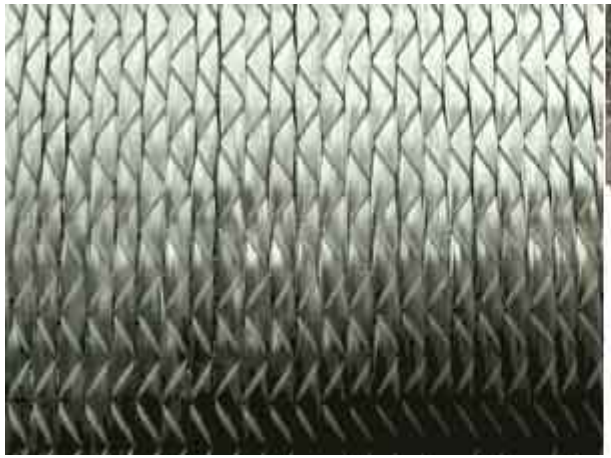


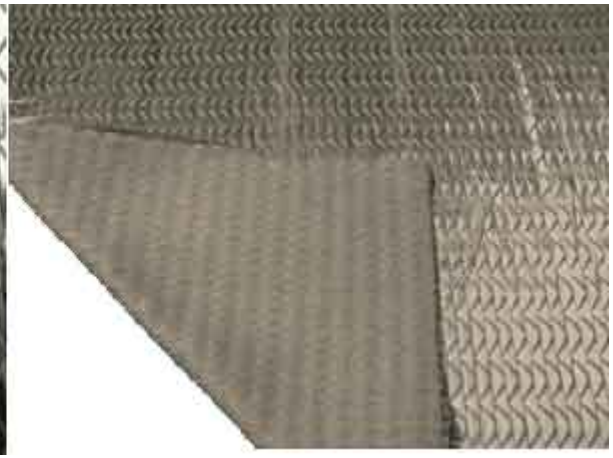
- Reinforcement composed of short fibers, randomly arranged, holding together by a binder.
- With the random orientation of fibers, the mat tends to be isotropic in the plane of the ply.
- **Advantages** : High permeability, ease of forming.
- **Drawbacks**: Low mechanical resistance, limited fiber volume content.

Structure of reinforcement: the UD



- In a UD, the fibers are parallel. There are sewed together with a light weft yarn





- Non balanced reinforcement

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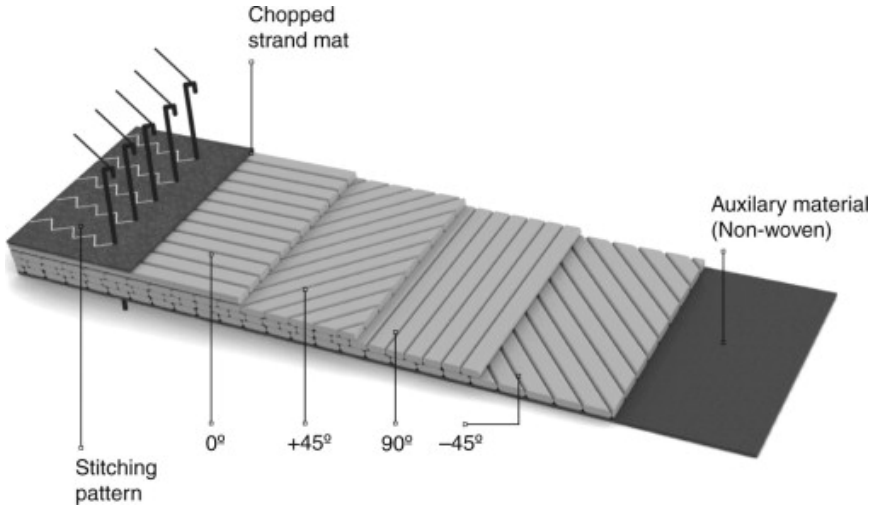
Non Crimped Fibers (NCFs) are a type of "engineered fabrics" to reinforce composites that are made up of multiple layers or fibers stitched together.
The most used NCF's are biaxial, triaxial and cuadriaxial fabrics, where the fiber tows are straight and with different orientations (0, 45, 90 degrees) to provide multidirectional properties.



Structure of reinforcement: the fabrics

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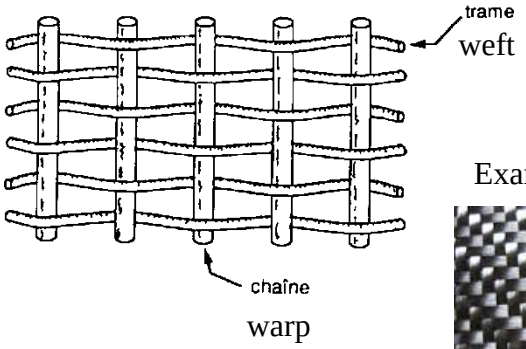
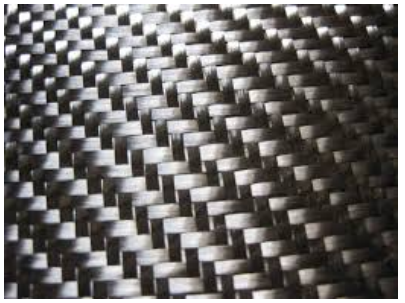
A fabric is a material consisting of fibers in two perpendicular directions:

The **Warp**: oriented along the length of the fabric

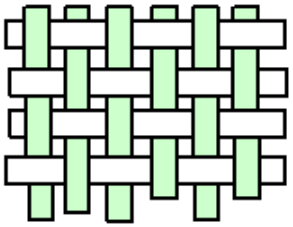
The **Weft**: perpendicular to the warp



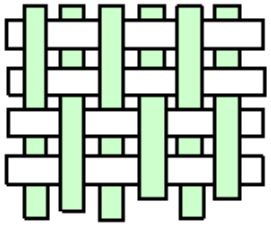
Example of carbon twill (3K)



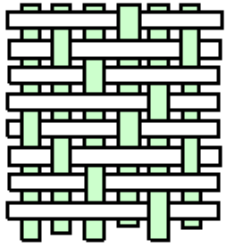
Fabrics are characterized by the mode of interlacing the warp and weft (weave).



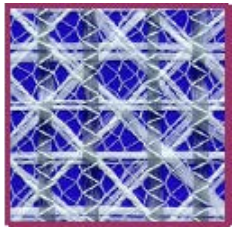
Taffeta
good flatness
Slightly deformable



Twill 2/2
More flexibility than the taffeta



Satin
Suitable for complex shapes



Multiaxial fabric

Advantages : The properties are located in the plane.
Drawbacks: Crimping of fibers, possible asymmetry, preforming difficult

III. Composites forming processes

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Liquid Composites Moulding (LCM)

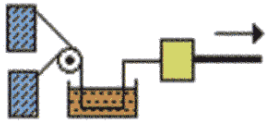
Contact molding, projection

Infusion

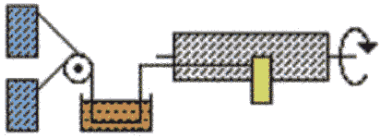
Resin Transfer Molding

Reactive injection Molding

Continuous processes

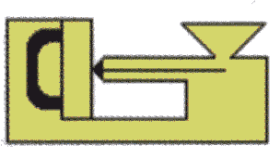


Pultrusion

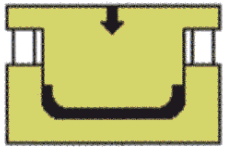


Filament winding

Semi-products forming (prepreg)

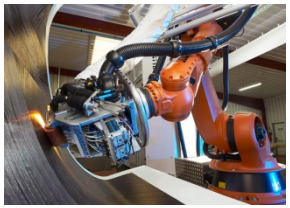


Injection Transfer Molding



Compression BMC, SMC

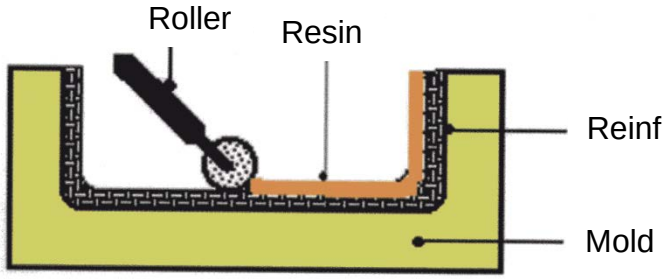
Prepreg + autoclave



Tape placement / AFP (Automated Fiber Placement)

The oldest ones

Hand lay-up

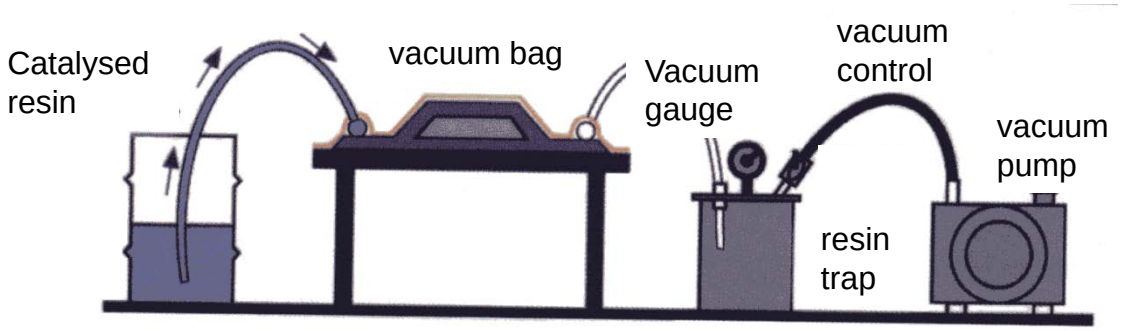


Projection

Main drawbacks :

- Long cycle time
- Good aspect only on one-side of the part
- Emanation of VOCs (Volatile Organic Compounds)
- No control

Infusion moulding



Wind turbine

Sailboat hulls and decks

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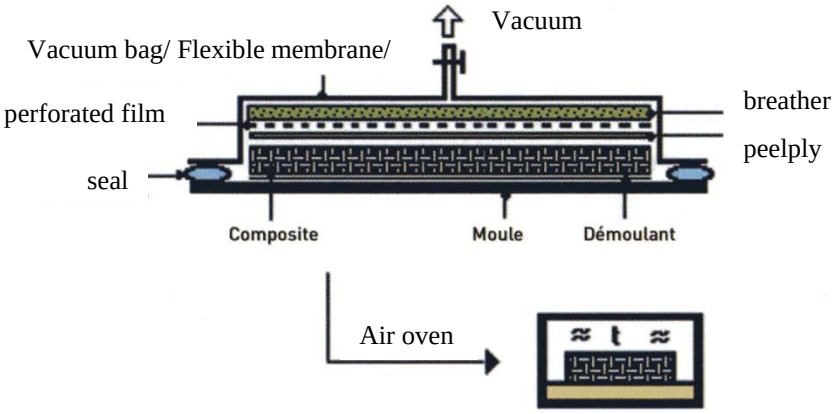
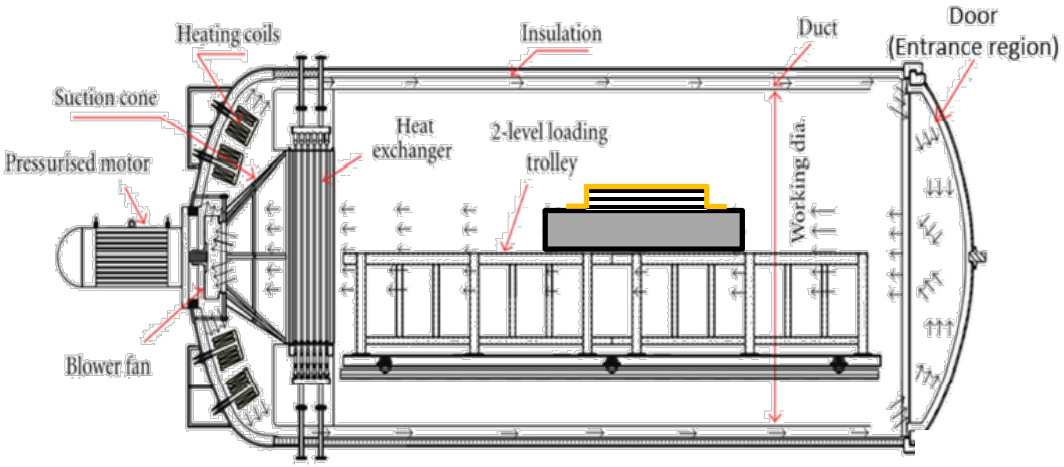
Automated Fiber Placement (AFP)

Airplane fuselage pannels

Consolidation under vacuum



Autoclave



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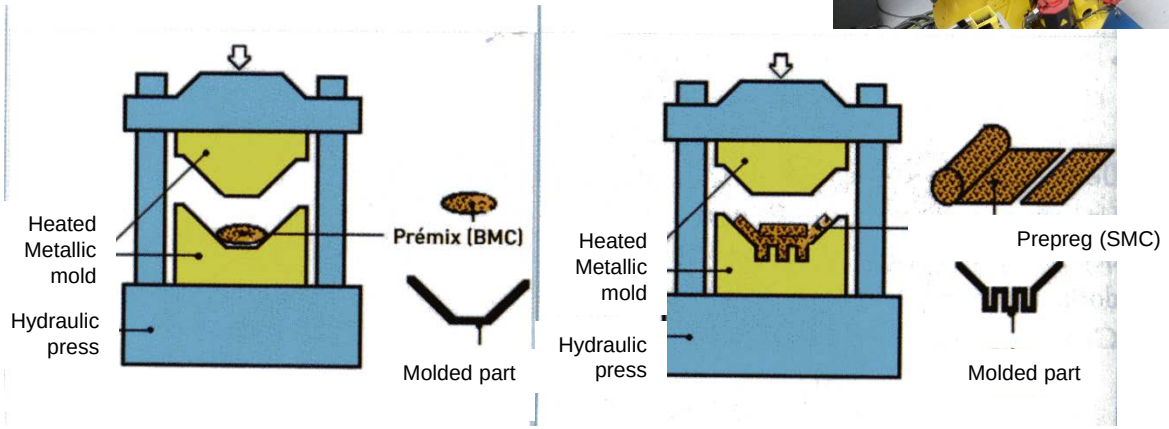
BMC : Bulk Molding Compound
SMC : Sheet Molding Compound

SMC compression



Applications :
BMC : Thick parts, electrical insulators..
SMC : Automobile (car radiator grille, car hood, hatchback, roof, floor, trucks's cabin

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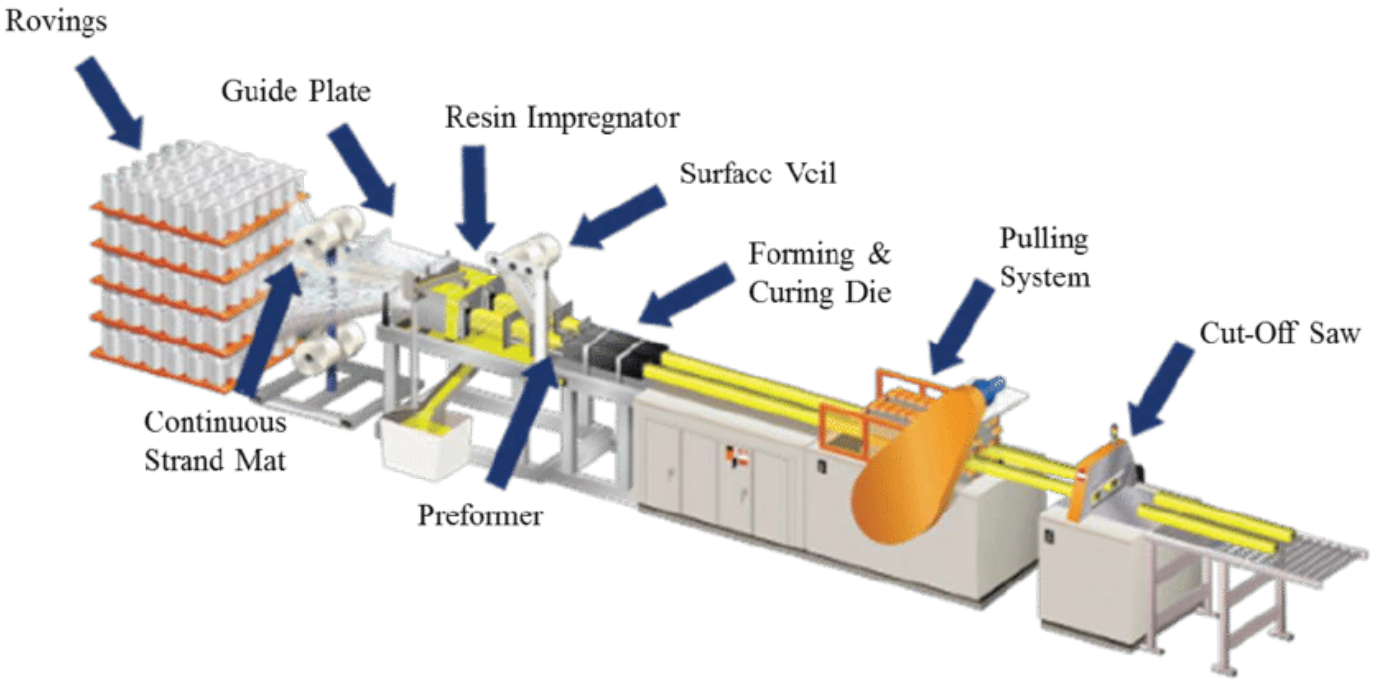
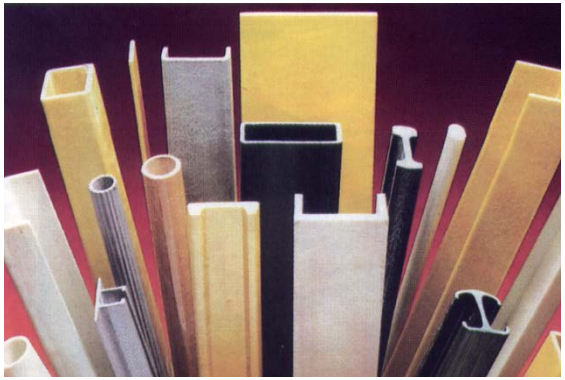


Applications : profile



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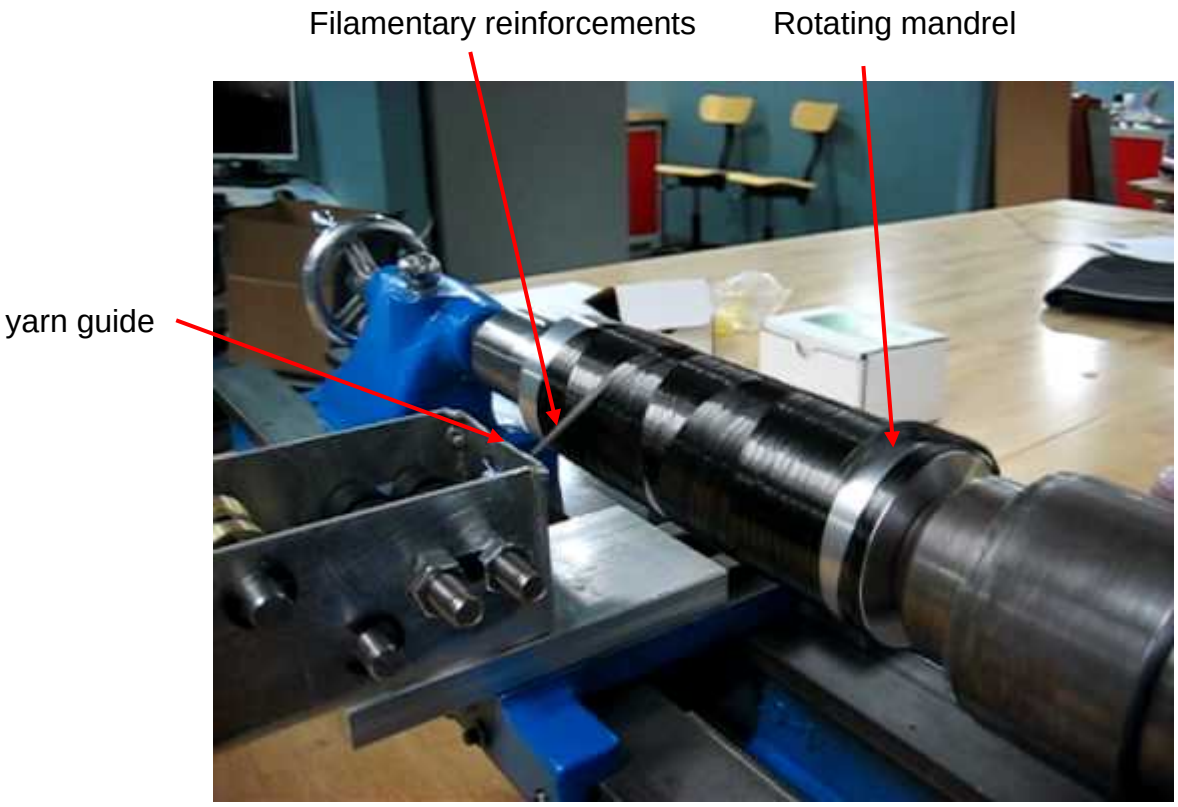

Applications: Tubes, tank, silo, helicopter blades, missile body

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IV. Common issues on processes

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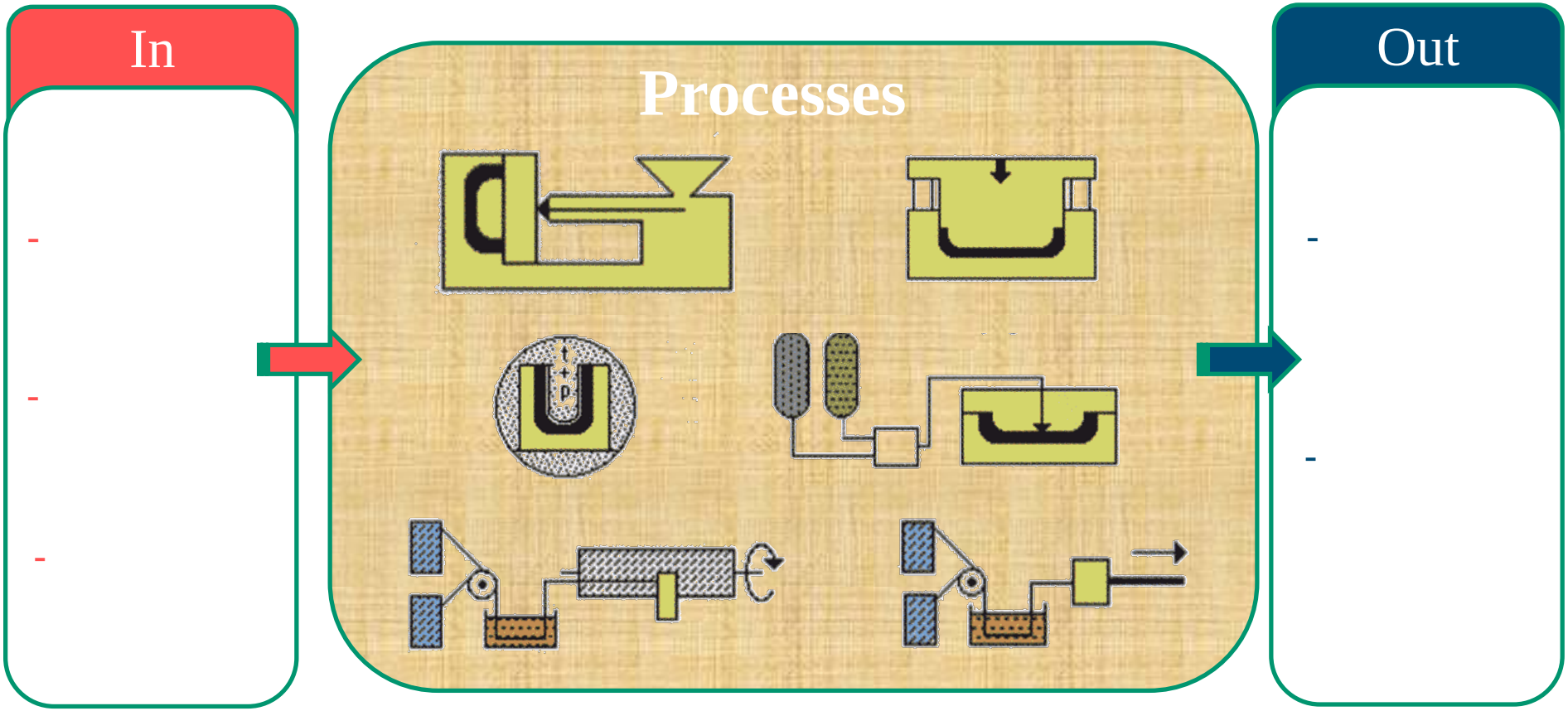
Depending on the specifications for the part :

- **Choice of the matrix and reinforcement**
- **Choice of the process**



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Supply and release of heat for the forming of thermosetting and thermoplastic composites

Material matrix	Heat supply (forming)	Heat release (consolidation)
Amorphous thermoplastics	T > Tg	T < Tg
Semi-crystalline thermoplastics	Melting	Crystallization
Thermosetting	↘ viscosity ↗ Reaction rate	↘ temperature ↘ cycle time
Reactive thermoplastics	Melting of the monomer Crosslinking	Crystallization (or not if amorphous)

1st remark: Heat transfers are required for composite forming

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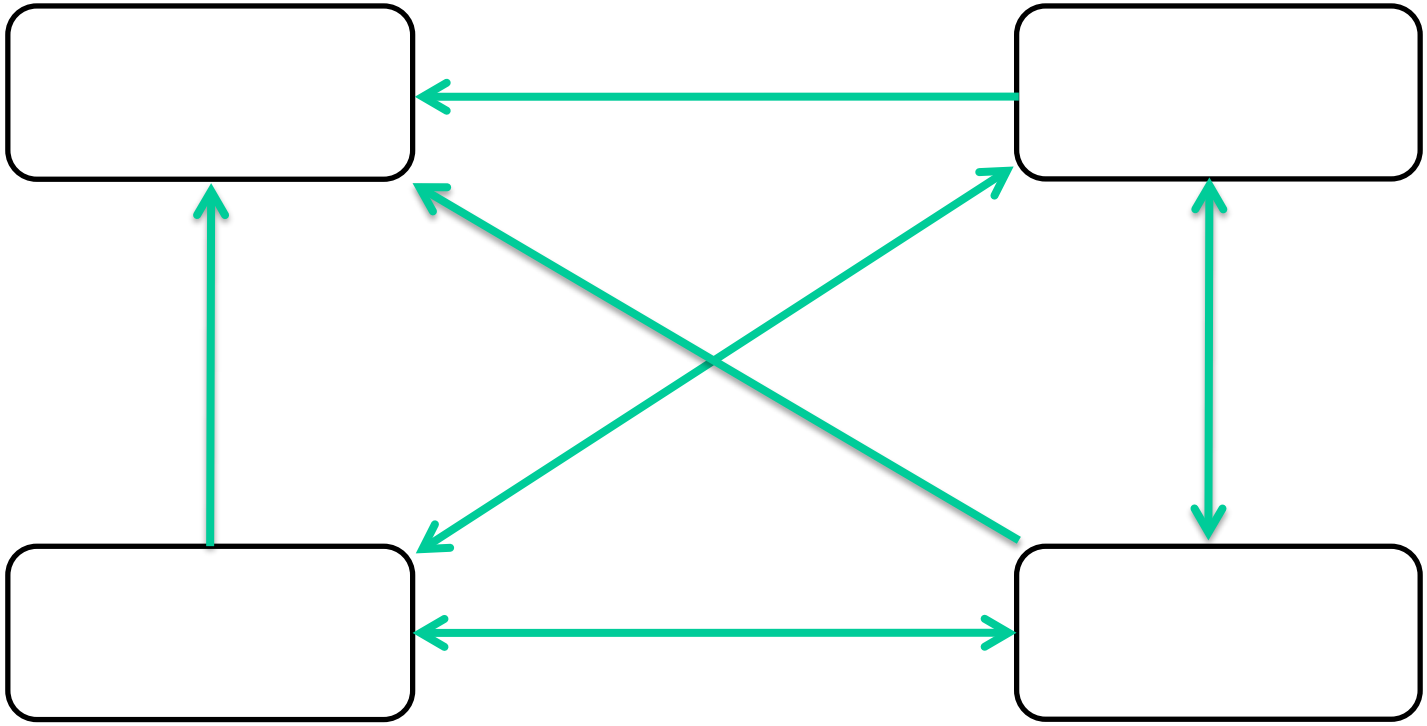

2nd remark: Heat transfer is a lever to control the forming of the parts

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Tableau 1 – Ordre de grandeur des caractéristiques thermophysiques de divers matériaux usuels						
Matériau	Conductivité thermique K ($W \cdot m^{-1} \cdot K^{-1}$)	Masse volumique ρ ($10^3\ kg \cdot m^{-3}$)	Capacité thermique C ($kJ \cdot kg^{-1} \cdot K^{-1}$)	Diffusivité thermique $a = \frac{K}{\rho C}$ ($mm^2 \cdot s^{-1}$)	Effusivité thermique $b = \sqrt{K\rho C}$ ($kW \cdot m^{-2} \cdot s^{1/2} \cdot K^{-1}$)	Coefficient de dilatation thermique α ($10^{-6}\ K^{-1}$)
Alliages de cuivre	50 à 230	7,5 à 9	0,32 à 0,4	17 à 80	12 à 26	14 à 17
Alliages d'aluminium	88 à 160	2,6 à 2,9	0,92 à 0,96	33 à 60	15 à 21	20 à 24
Aciers	24 à 66	7,6 à 8,1	0,42 à 0,5	7 à 19	9 à 15	11 à 12
Pierre	1,2	2	0,835	0,7	1,3	2 à 5
Graphite	120 à 200	1,82	0,12	550 à 915	5,1 à 6,6	2,5
Verre (amorphe)	1,2 à 1,6	2,2 à 2,5	0,8 à 1	0,5 à 0,75	1,5 à 1,8	4,5 à 8,5
Thermoplastiques	0,15 à 0,35	0,9 à 2,2	1 à 2,2	0,05 à 0,2	0,5 à 0,8	50 à 300
Résines	0,15	1,2 à 1,4	1,7 à 2	0,06	0,6	25 à 90
Bois	0,12	0,4	1,25	0,25	0,25	3 à 30

Techniques de l'ingénieur

Usure des polymères **AM 3 136**

Aspects thermiques et applications

Thermal control remains tricky because composites are insulating materials

Application : how is this part manufactured?

V. Resin Transfer Molding Process (RTM)

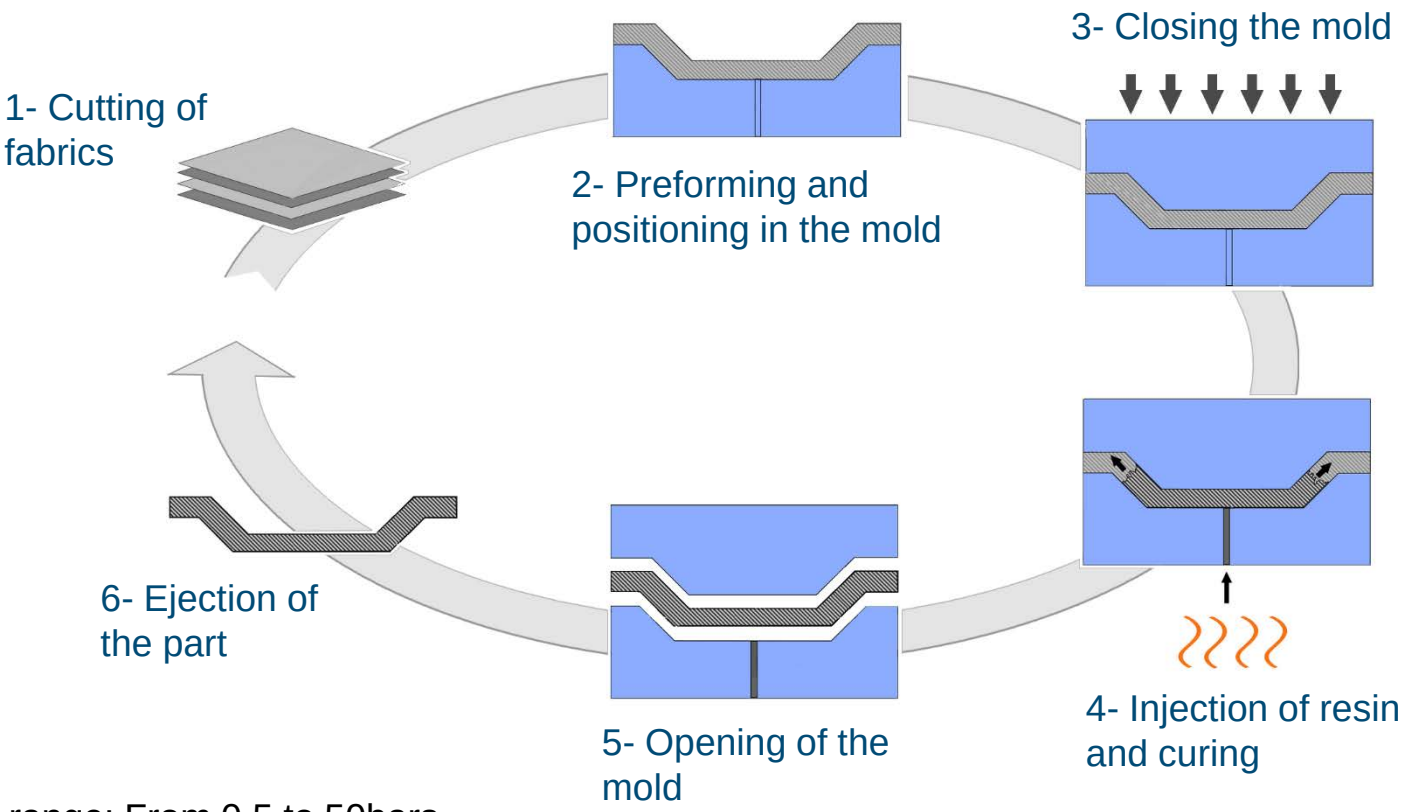
POLYTECH NANTES

- The largest category is called LCM: Liquid Composite Molding (RTM belongs to LCM)

- First traces of RTM : in the forties, but real development in the 70s (automobile industry)
  - Improves quality and productivity
  - Enables the integration of function (inserts), the manufacturing of sandwich structures…
  - Allows a better control during the process
  - Limits VOC (Volatile organic compound) emissions (Legislation)

POLYTECH NANTES

Definition: Injection at low pressure of a thermosetting resin into a dry preform placed inside a closed mold.



Pression range: From 0.5 to 50bars
Thickness : From 2mm to 40mm

POLYTECH NANTES

$$\overrightarrow{u_w} = -\frac{k_{rw}(S)\,\bar{\bar{K}}}{\mu_w}\,\vec{\nabla}P_w \qquad \frac{\partial \alpha}{\partial t} = f(\alpha, T)$$

Flow

Chemistry

Mechanics

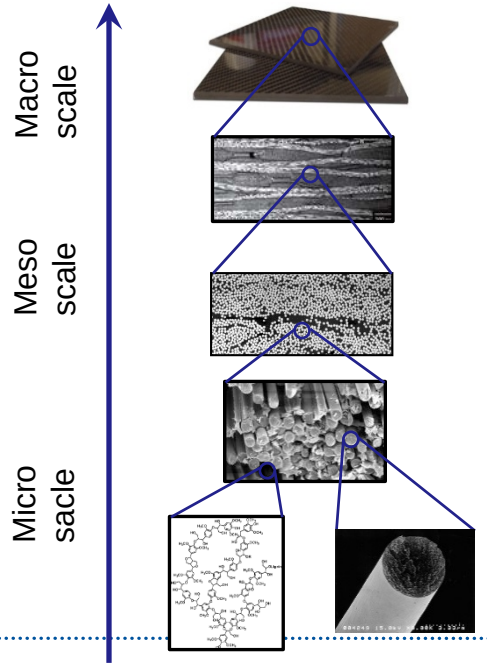
$$\bar{\bar{\sigma}} = \overline{\overline{\overline{C(T,\alpha)}}} : \left[\bar{\bar{\varepsilon}} - \overline{\overline{CTE(T,\alpha)}}(T - T_{ini}) - \overline{\overline{CCS(T,\alpha)}}(\alpha - \alpha_{ini})\right]$$

Heat transfer

$$(\rho_c Cp_c)\frac{\partial T}{\partial t} + (\phi \rho_r Cp_r)\overrightarrow{u_w}\left(\overrightarrow{\nabla T} + \overrightarrow{\nabla \alpha}\right) = \overrightarrow{\nabla} \cdot \left(\overline{\overline{\lambda_c}}\,\overrightarrow{\nabla T}\right) + (\phi)\rho_r \Delta H \frac{\partial \alpha}{\partial t}$$

Complex materials:

- **Anisotropics**
- **Multi-scales**



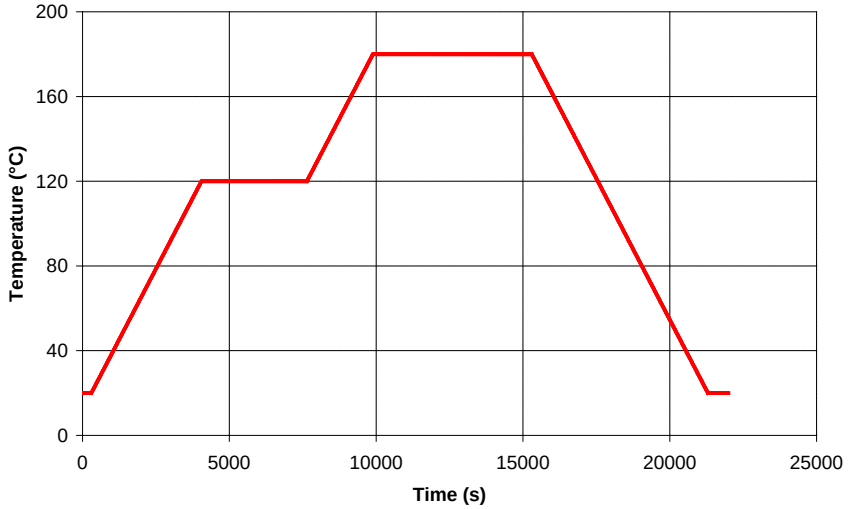
- Coupled phenomena
- Heterogeous materials
- Properties dependant of state of material

→ Simplifying assumptions

POLYTECH NANTES

Specifications:

- Thermal cycle to impose to the part

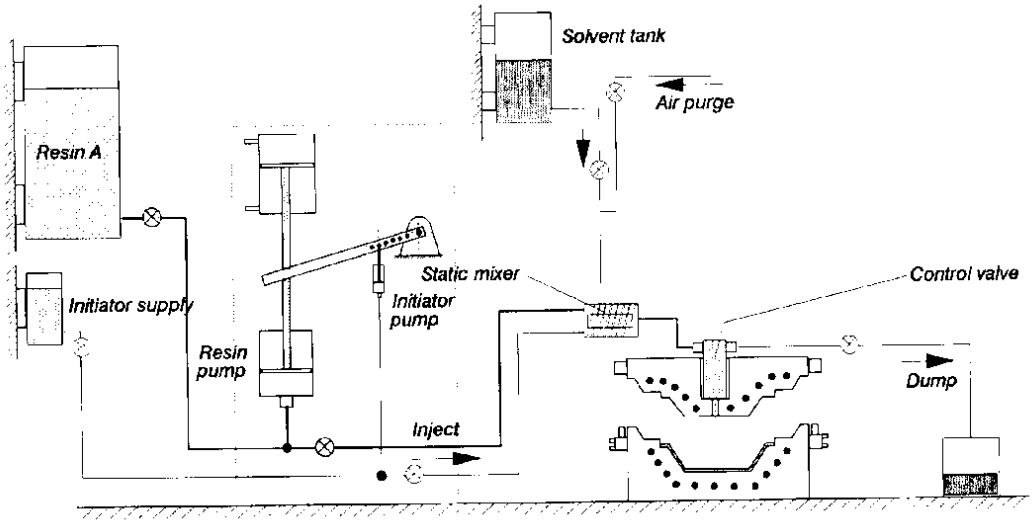


- Filling time : 30min at 120°C

Determine :

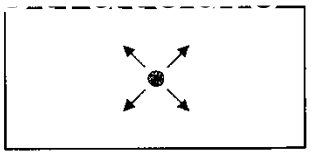
- Flow rate of resin / Pressure inside the mold during filling
- Predict the curing time
- Design the heat control system of the mold

The injection system

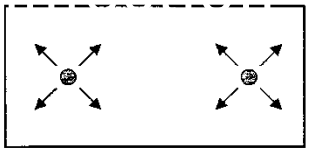


POLYTECH NANTES

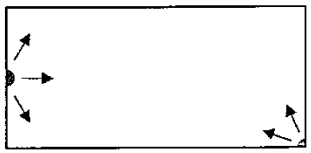
Positionning of injection points and vents



single internal injection port

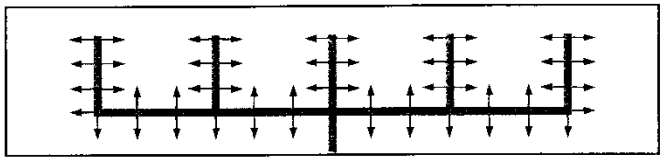


multiple internal injection port

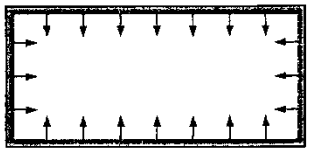


external injection port

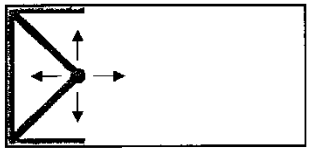
injection line



tree-like injection channel



peripheral injection

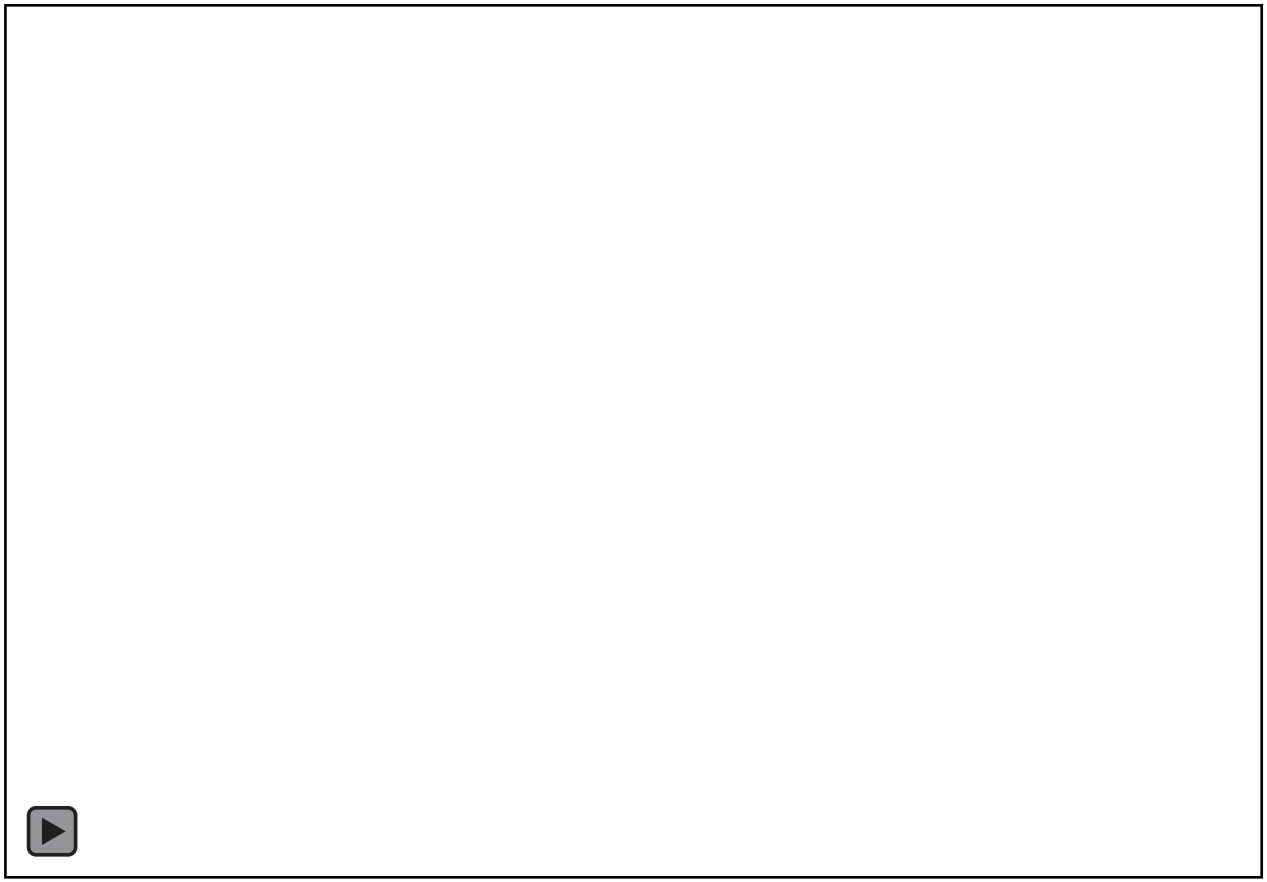


combination of single injection port with runners

- It is essential to analyze and study the shape and location of the injection zones in order to achieve complete parts and avoid air traps and dry spots.
- They are calculated so as to inject all of the resin in a given time, and especially to fill the mold.

POLYTECH NANTES

Filling: calculation of the required flow rate

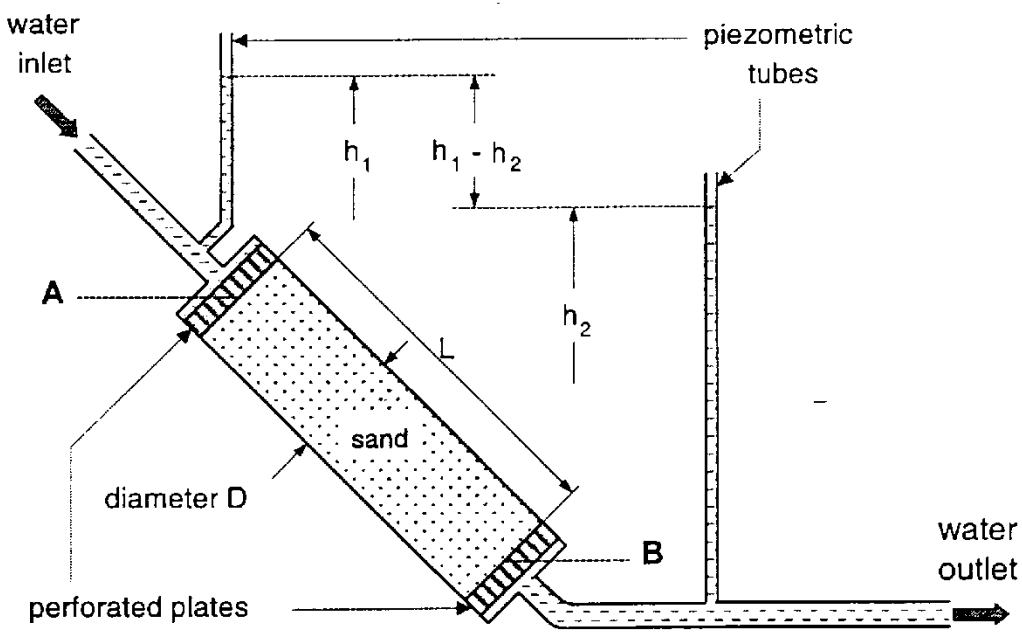


→Simplifying assumption: isothermal filling with no phase change

VI. The law of Darcy

POLYTECH NANTES

Darcy's experiment



The first studies of this type of flow were carried out by Henry Darcy on the sand filters of the funtains in Dijon in 1856

Darcy's law

Average speed

Permeability

$$\overline{U} = -\frac{\overline{\overline{K}}}{\mu}\nabla p$$

Fluid vscosity

Pressure

Permeability: The capability of a porous medium to permit the flow of fluids through its pore spaces. This is an intrinsic characteristic of the material independent of the fluid (unit m^2).

$$\begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = -\frac{1}{\mu} \begin{bmatrix} \mathbf{K_{xx}} & \mathbf{K_{xy}} & \mathbf{K_{xz}} \\ \mathbf{K_{xy}} & \mathbf{K_{yy}} & \mathbf{K_{yz}} \\ \mathbf{K_{xz}} & \mathbf{K_{yz}} & \mathbf{K_{zz}} \end{bmatrix} . \begin{bmatrix} \frac{\partial p}{\partial x} \\ \frac{\partial p}{\partial y} \\ \frac{\partial p}{\partial z} \end{bmatrix}$$

Continuity equation (mass conservation)

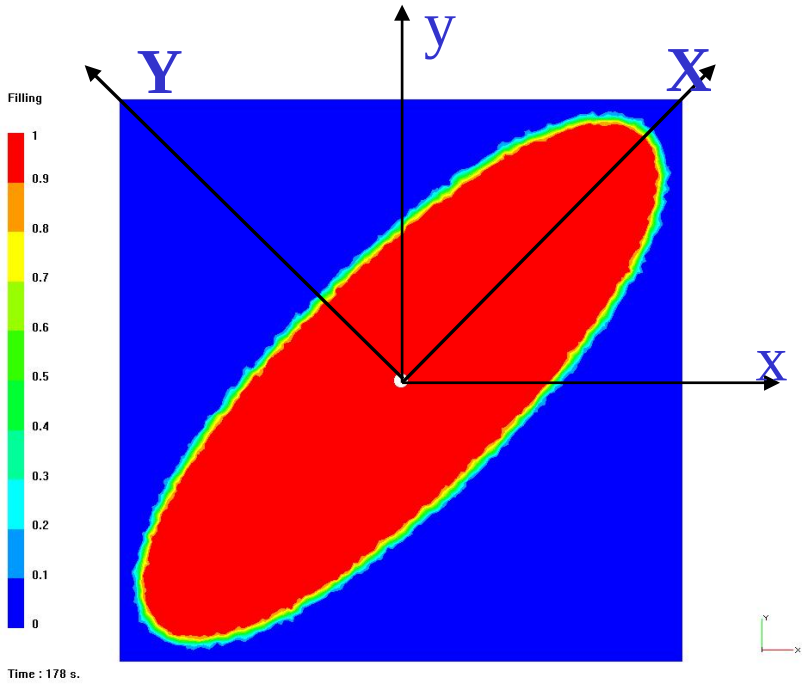
$$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho \overline{U}\right) = 0$$

If $\rho = cte \rightarrow \nabla.\overline{U} = 0$ ⇒ $\frac{\partial U_x}{\partial x} + \frac{\partial U_y}{\partial y} + \frac{\partial U_z}{\partial z} = 0$

$$\begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = -\frac{1}{\mu} \begin{bmatrix} \mathbf{K_{xx}}\frac{\partial p}{\partial x} + \mathbf{K_{xy}}\frac{\partial p}{\partial y} + \mathbf{K_{xz}}\frac{\partial p}{\partial z} \\ \mathbf{K_{xy}}\frac{\partial p}{\partial x} + \mathbf{K_{yy}}\frac{\partial p}{\partial y} + \mathbf{K_{yz}}\frac{\partial p}{\partial z} \\ \mathbf{K_{xz}}\frac{\partial p}{\partial x} + \mathbf{K_{yz}}\frac{\partial p}{\partial y} + \mathbf{K_{zz}}\frac{\partial p}{\partial z} \end{bmatrix}$$

⇒ Analytical solving difficult

Principal permeabilities



In any basis (x,y,z)

$$\begin{bmatrix} \mathbf{K_{xx}} & \mathbf{K_{xy}} & \mathbf{K_{xz}} \\ \mathbf{K_{xy}} & \mathbf{K_{yy}} & \mathbf{K_{yz}} \\ \mathbf{K_{xz}} & \mathbf{K_{yz}} & \mathbf{K_{zz}} \end{bmatrix}$$

In the principal basis (**X**,**Y**,**Z**)

$$\begin{bmatrix} \mathbf{K_x} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K_y} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{K_z} \end{bmatrix}$$

Darcy's equation is then written:

$$\begin{bmatrix} U_X \\ U_Y \\ U_Z \end{bmatrix} = -\frac{1}{\mu} \begin{bmatrix} \mathbf{K_x} \dfrac{\partial p}{\partial X} \\ \mathbf{K_y} \dfrac{\partial p}{\partial Y} \\ \mathbf{K_z} \dfrac{\partial p}{\partial Z} \end{bmatrix}$$

$$\nabla.\overline{U} = -\frac{1}{\mu}\left(\frac{\partial \mathbf{K_x}}{\partial X}\frac{\partial p}{\partial X} + \mathbf{K_x}\frac{\partial^2 p}{\partial X^2} + \frac{\partial \mathbf{K_y}}{\partial Y}\frac{\partial p}{\partial Y} + \mathbf{K_y}\frac{\partial^2 p}{\partial Y^2} + \frac{\partial \mathbf{K_z}}{\partial Z}\frac{\partial p}{\partial Z} + \mathbf{K_z}\frac{\partial^2 p}{\partial Z^2}\right)$$

If the material is homogenous: K_X, K_Y, K_Z are independant of the position : $\frac{\partial \mathbf{K_i}}{\partial i} = 0$

$$\nabla.\overline{U} = -\frac{1}{\mu}\left(\mathbf{K_x}\frac{\partial^2 p}{\partial X^2} + \mathbf{K_y}\frac{\partial^2 p}{\partial Y^2} + \mathbf{K_z}\frac{\partial^2 p}{\partial Z^2}\right)$$

If, in addition, the material is isotropic : $K_X=K_Y=K_Z=K$

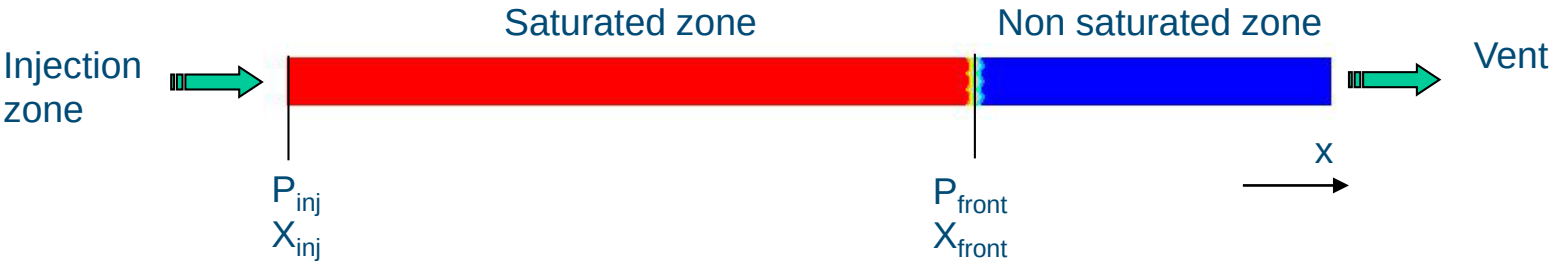
$$\nabla.\overline{U} = -\frac{\mathbf{K}}{\mu}\left(\frac{\partial^2 p}{\partial X^2} + \frac{\partial^2 p}{\partial Y^2} + \frac{\partial^2 p}{\partial Z^2}\right)$$

$$\nabla.\overline{U} = -\frac{\mathbf{K}}{\mu}\Delta P$$

$$\boxed{\text{Or } \nabla.\overline{U} = 0, \text{ donc } \Delta P = 0}$$

In the principal basis, in case of an homogenous and isotropic material with ρ=constant

1D flow: Injection at constant pressure



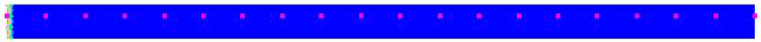
Permeability of the reinforcement in flow direction : K (m²)
Viscosity of the resin: μ (Pa.s)

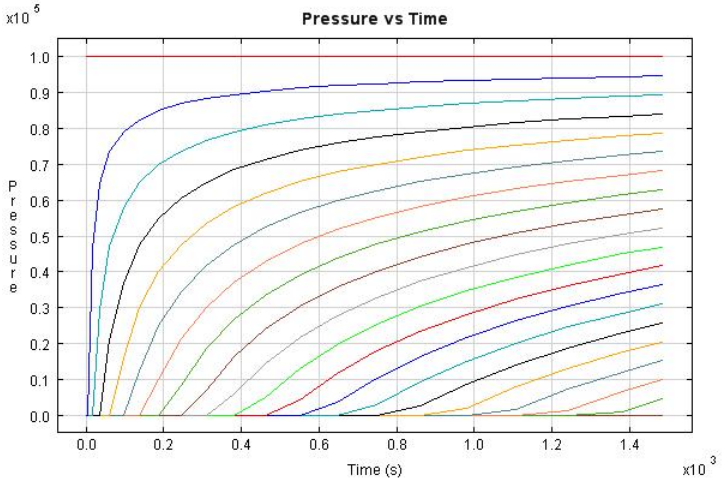
$$\Delta P = 0 \Rightarrow \frac{\partial^2 P}{\partial x^2} = 0 \Rightarrow P(x) = \left(P_{front} - P_{inj}\right)\frac{x - x_{inj}}{x_{front} - x_{inj}} + P_{inj}$$

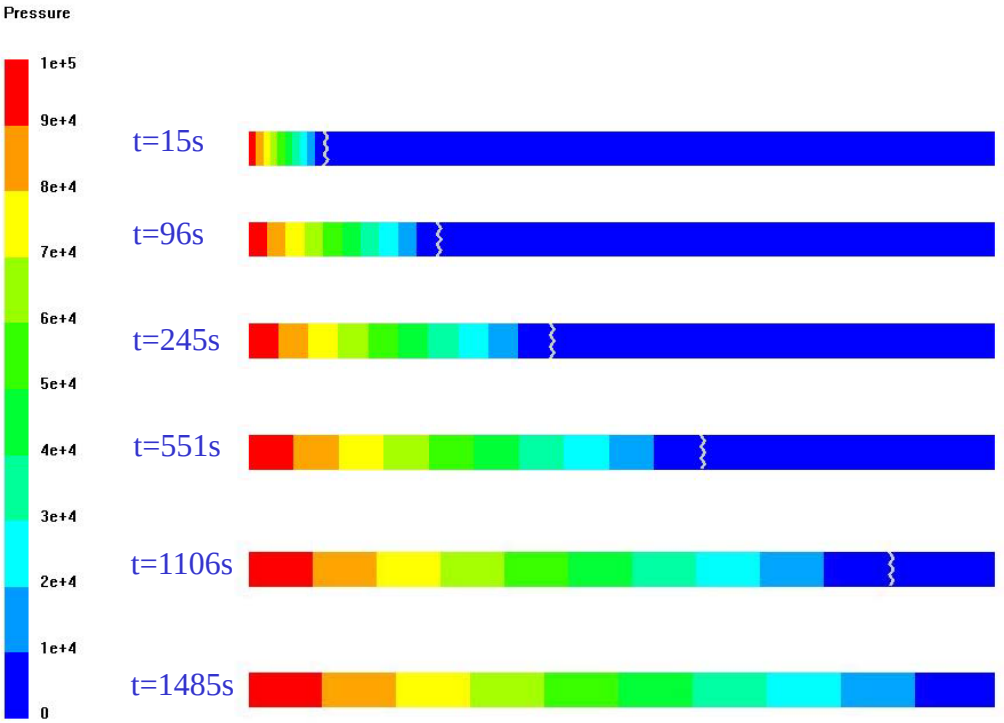
1D flow: Injection at constant pressure

At each instant the pressure gradient is constant in the part

$$\nabla P = \frac{P_{front} - P_{inj}}{x_{front} - x_{inj}}$$







POLYTECH NANTES

Average flow speed

$$U(t) = -\frac{K}{\mu}\frac{P_{front} - P_{inj}}{x_{front}(t) - x_{inj}}$$

Average speed in the flow (U) ≠ fluid flow (V)

$$V = \frac{U}{\phi}$$

ϕ : porosity of the medium, parameter that varies between 0 and 1

ϕ=0 → Solid medium

ϕ=1→ Fluid medium

ϕ =1- τ_v ,with τ_v volume fiber content

NB: porosity ≠ permeability

$$\tau_v = \frac{\text{fibre volume}}{\text{total volume}}$$

POLYTECH NANTES

Uniform speed in the flow

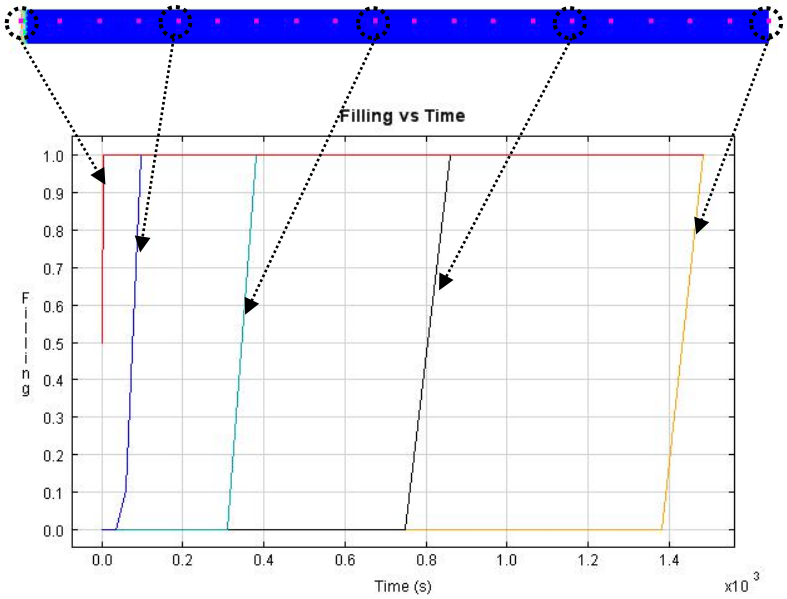
$$V = \frac{dx}{dt} = \frac{U}{\phi}\ ,\ \forall P \in \left[x_i, x_f\right]$$

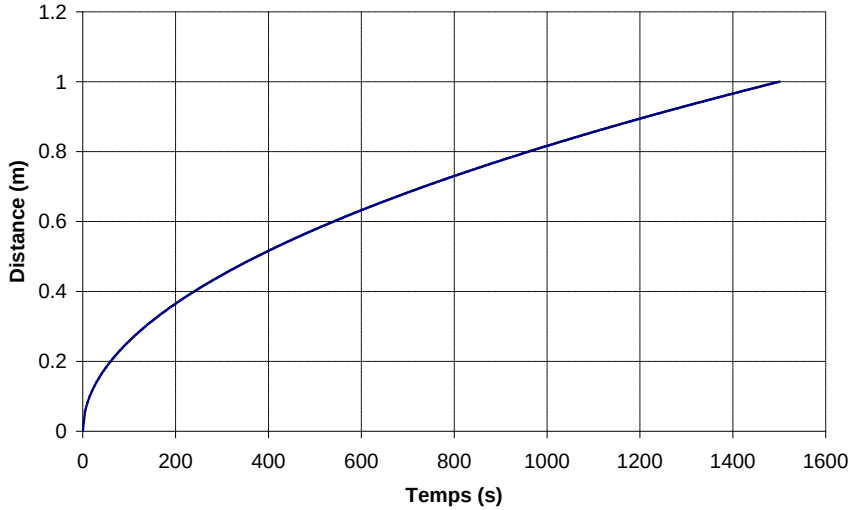
$$V_f = \frac{dx_f}{dt}$$

$$\frac{dx_f}{dt} = -\frac{K}{\mu\phi}\frac{P_f - P_i}{x_f - x_i}$$

1D flow: Injection at constant pressure

$$x_f = \sqrt{\frac{2K}{\mu\phi}\left(P_i - P_f\right)t}$$

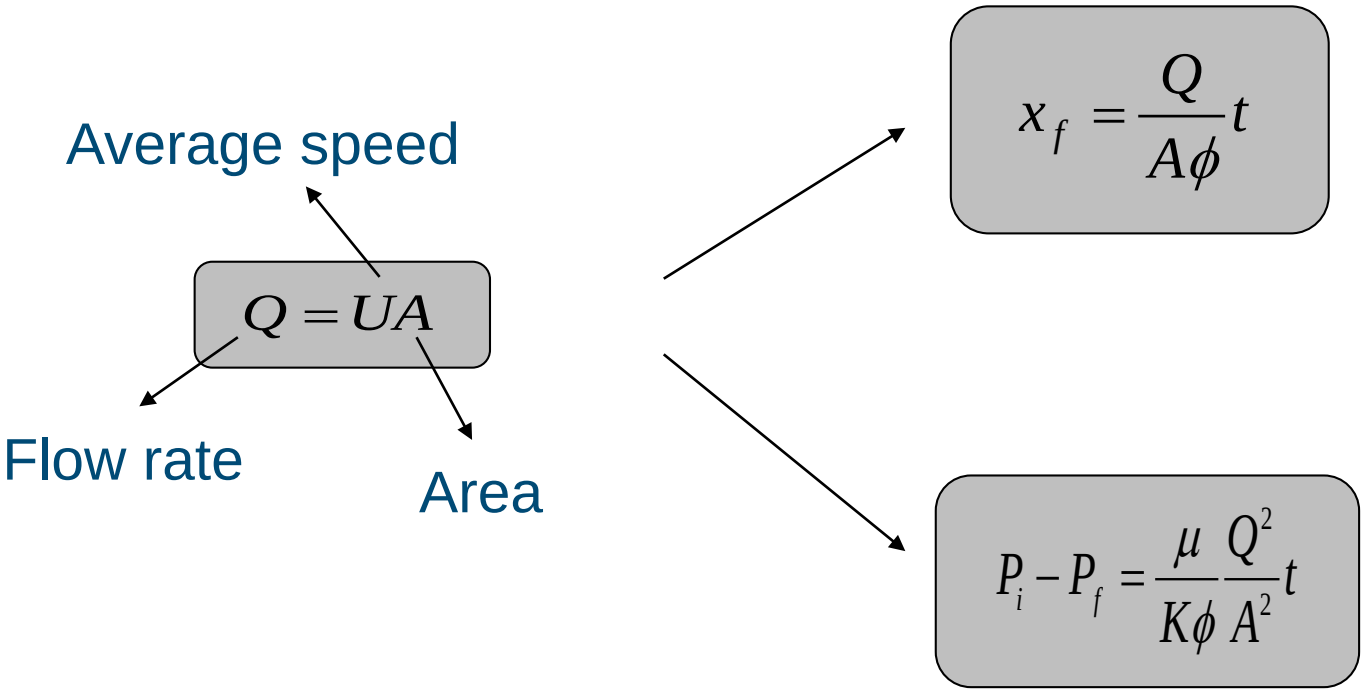




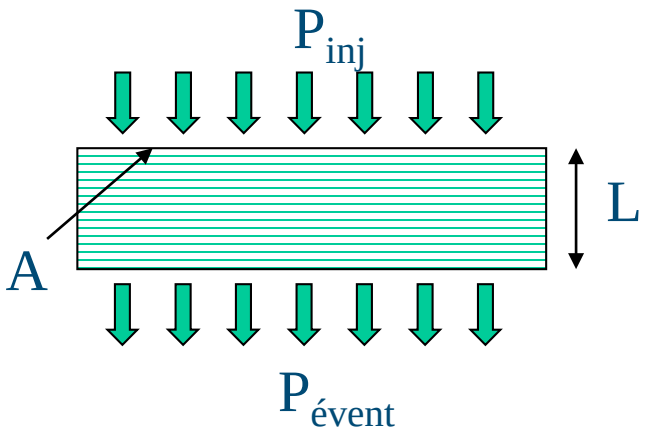
$$x_{C1} = 0.0000m \rightarrow t_{C1} = 0s$$
$$x_{C2} = 0.2105m \rightarrow t_{C2} = 66s$$
$$x_{C3} = 0.4737m \rightarrow t_{C3} = 337s$$
$$x_{C4} = 0.7368m \rightarrow t_{C4} = 814s$$
$$x_{C5} = 1.0000m \rightarrow t_{C4} = 1500s$$

$$\begin{cases} K = 10^{-10}\,m^2 \\ \mu = 0.1Pa.s \\ \phi = 0.3 \\ P_i = 2.10^5\,Pa \\ P_f = 1.10^5\,Pa \end{cases}$$

1D flow: injection at constant flow rate



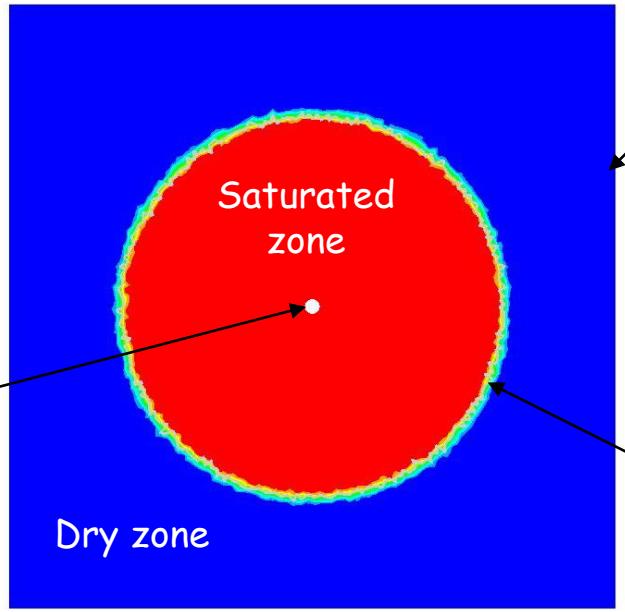
Determination of the transverse (through thickness) permeability:



$$Q = \frac{AK}{\mu}\frac{P_{inj} - P_{évent}}{L}$$

2D flow: Injection at constant pressure

At a given time:



Vent: edges of the part

P_{inj}
r_{inj}

P_{front}
r_{front}

$$\Delta P = 0 \Rightarrow \frac{1}{r}\frac{d}{dr}\left(r\frac{dP}{dx}\right) = 0 \Rightarrow P(r) = \left(P_{front} - P_{inj}\right)\frac{\ln r - \ln r_{inj}}{\ln r_{front} - \ln r_{inj}} + P_{inj}$$

2D flow: Injection at constant pressure

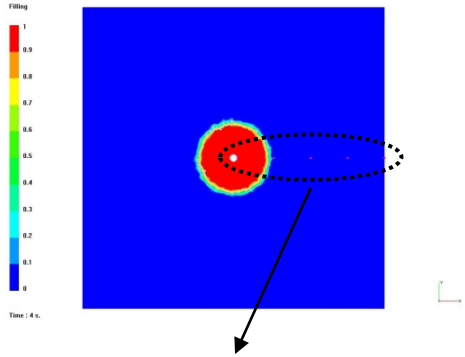
$$\nabla P = \frac{P_{front} - P_{inj}}{\ln r_{front} - \ln r_{inj}} \frac{1}{r}$$

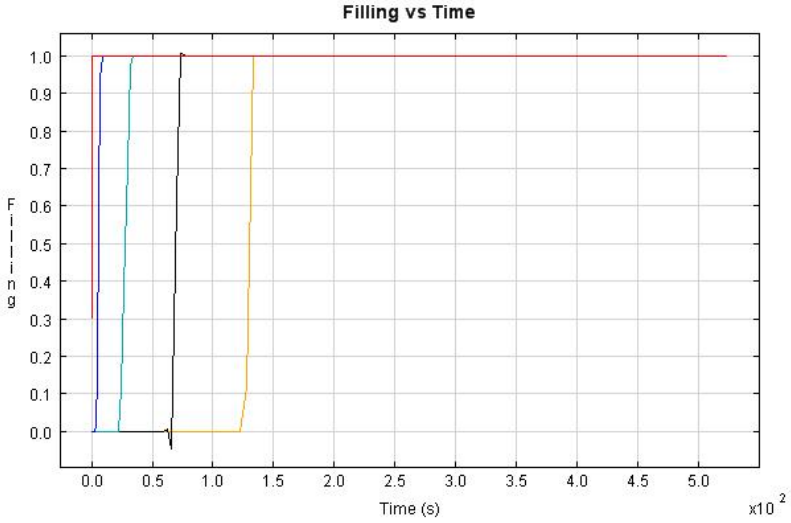
Darcy's law is written: $\frac{dr}{dt} = -\frac{K}{\mu\phi} \frac{P_{front} - P_{inj}}{\ln r_{front} - \ln r_{inj}} \frac{1}{r}$, $\forall r \in \left[r_i, r_f\right]$

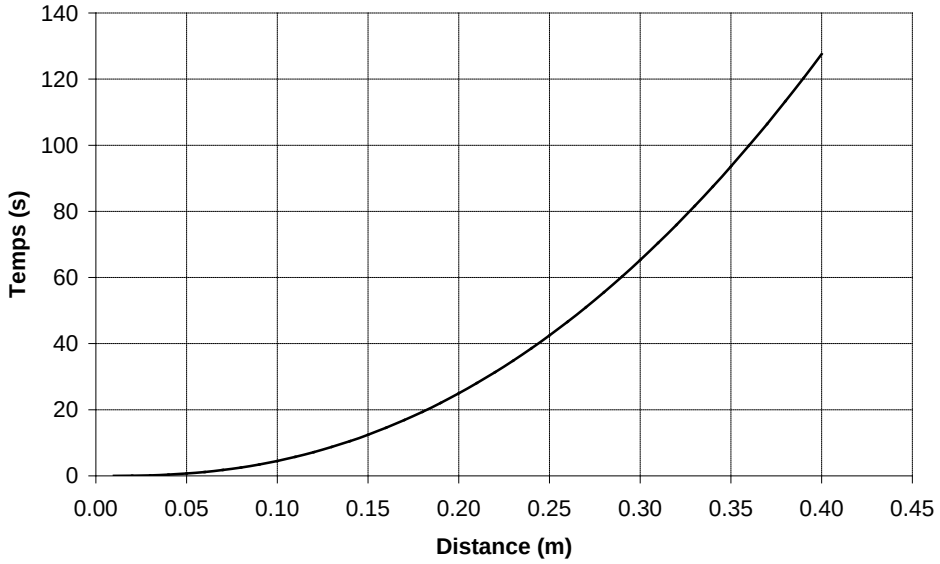
For $r=r_{front}$: $\frac{dr_{front}}{dt} = -\frac{K}{\mu\phi} \frac{P_{front} - P_{inj}}{\ln r_{front} - \ln r_{inj}} \frac{1}{r_{front}}$

$$r_f^2 \left(2 \ln \frac{r_f}{r_i} - 1 \right) + r_i^2 = \frac{4K}{\mu\phi} \left(P_i - P_f \right) t$$

2D flow: Injection at constant pressure







$$x_{C1} = 0.0100m \rightarrow t_{C1} = 0s$$
$$x_{C2} = 0.1075m \rightarrow t_{C2} = 5s$$
$$x_{C3} = 0.2050m \rightarrow t_{C3} = 27s$$
$$x_{C4} = 0.3025m \rightarrow t_{C4} = 66s$$
$$x_{C5} = 0.4000m \rightarrow t_{C4} = 128s$$

$$\begin{cases} K = 10^{-9} m^2 \\ \mu = 0.1 Pa.s \\ \phi = 0.5 \\ P_i = 2.10^5 Pa \\ P_f = 1.10^5 Pa \end{cases}$$

2D flow: Injection at constant flow rate

Average speed

$$Q = UA$$

Flow rate

Area

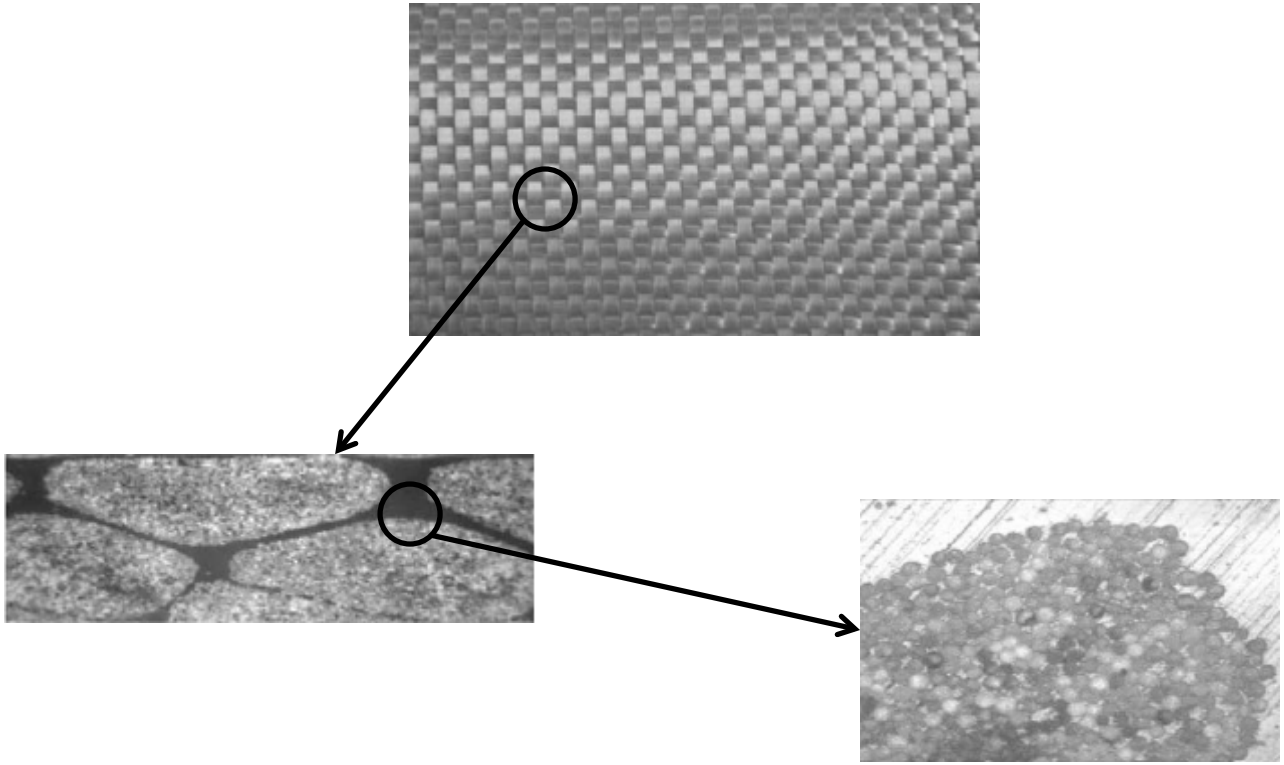
$$A = 2\pi r_f h$$

$$Q = 2\pi r_f h\phi \frac{dr_f}{dt}$$

$$r_f = \sqrt{\frac{Qt}{\pi h\phi} + r_i^2}$$

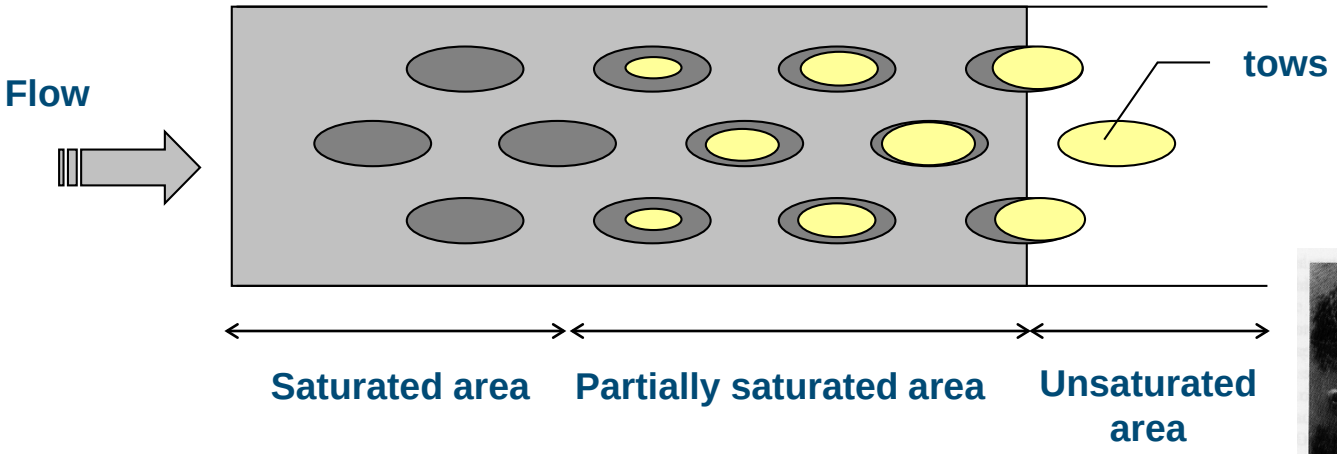
$$P_i - P_f = \frac{Q\mu\Phi}{2\pi hK}\left[\frac{1}{2}\ln\left(\frac{Q}{\pi\phi h}t + r_i^2\right) - \ln r_i\right]$$

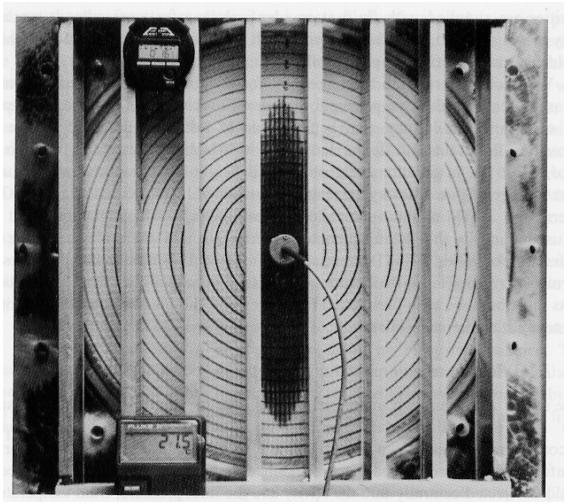
Limitation of the Darcy's law: Heterogeneity of the medium



Several scales in the material

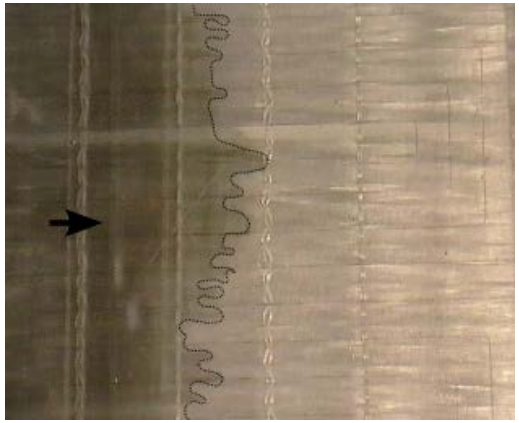
Heterogeneity of the medium





Behavior at two scales:

- Flow between the tows
- Flow inside the tows

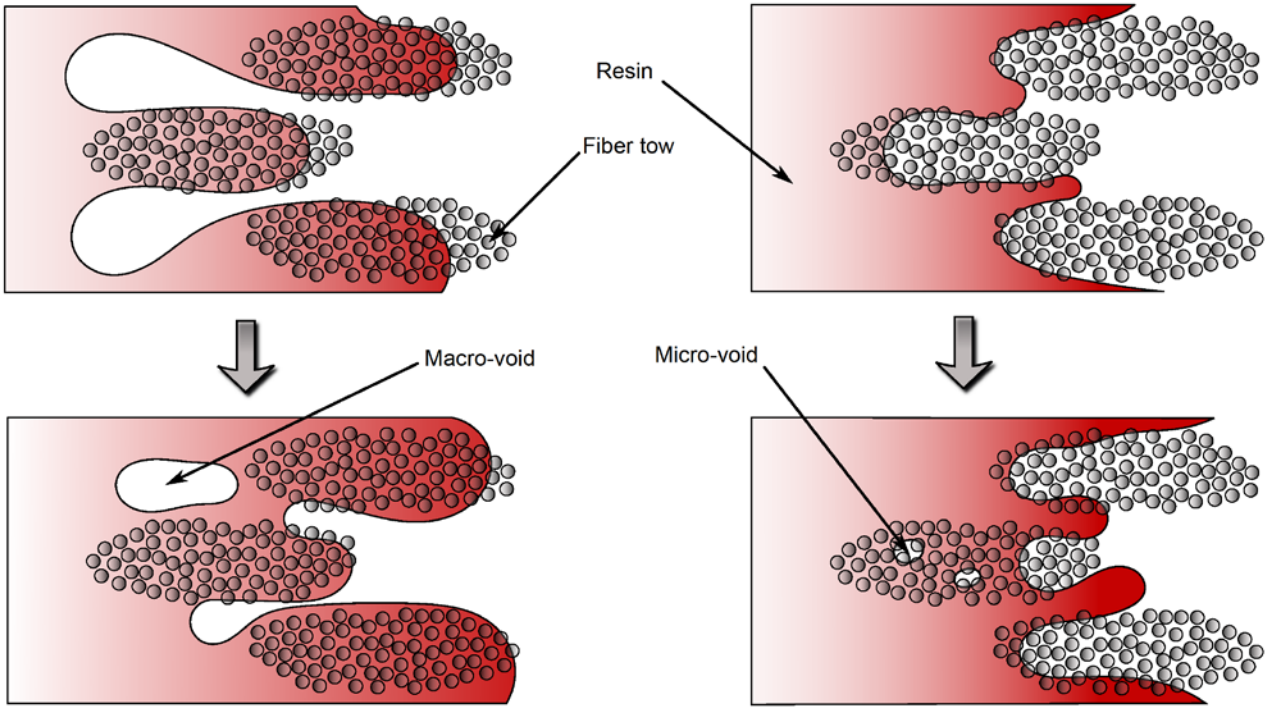


⇨ Limitation of Darcy→ describe only macroscopic flow

Permeability of saturated medium ≠ Permeability of the unsaturated medium

POLYTECH NANTES

→Creation of dry spots



POLYTECH NANTES

Definition of the **saturation** of the porous medium:

S=volume filled by the fluid / total volume that can be filled by the fluid
The saturation evolves between 0 and 1

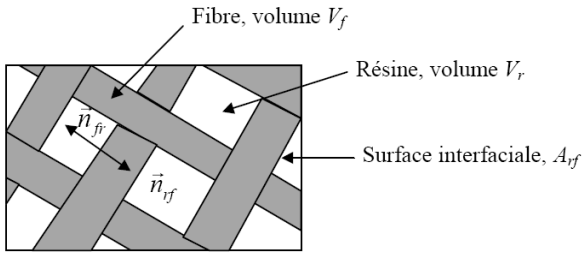
A weighting coefficient called relative permeability (k(s)) and dependant of the saturation is then defined. This parameter in introduced in the Darcy's law to take into account the partial saturation of the medium.

$$\overline{U} = -\frac{\overline{\overline{\mathbf{K}}}k(s)}{\mu}\nabla p$$

K corresponds to the permeability of the saturated medium

The question remains: How to characterize this relative permeability?

POLYTECH NANTES



Energy equation in the area filled by the resin

$$\rho_r Cp_r \left(\frac{\partial T_r}{\partial t} + v \nabla T_r \right) = \nabla . \left(\lambda_r \nabla T_r \right)$$

Energy equation in the area occupied by the fibers

$$\rho_f Cp_f \frac{\partial T_f}{\partial t} = \nabla . \left(\lambda_f \nabla T_f \right)$$

By averaging on a REV and by considering a one temperature model:

$$\underbrace{\left(\phi \rho_r Cp_r + (1-\phi) \rho_f Cp_f \right)}_{(\rho Cp)_e} \frac{\partial \langle T \rangle}{\partial t} + \phi \rho_r Cp_r \langle v \rangle \nabla \langle T \rangle = \nabla . \left(\left(\lambda_e + \lambda_d \right) \nabla \langle T \rangle \right)$$

Conductivity due to thermal dispersion

The thermal dispersion is due to spatial fluctuations of speed flow and of temperature at microscopic scale

VII. Heat transfer during curing

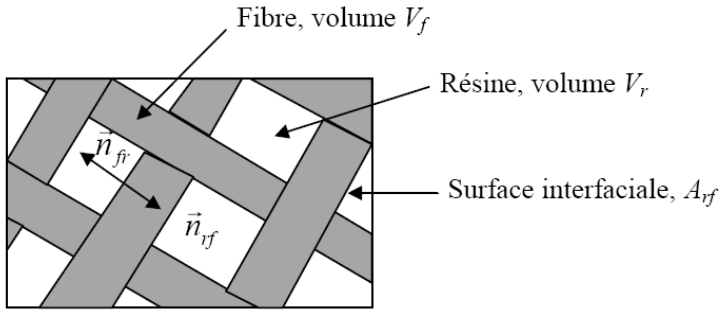
Analysis of the heat tansfer during the consolidation (without flow)

$$\underbrace{\left(\phi\rho_r Cp_r + (1-\phi)\rho_f Cp_f\right)}_{(\rho Cp)_e}\frac{\partial\langle T\rangle}{\partial t} + \phi\rho_r Cp_r\langle v\rangle\nabla\langle T\rangle = \nabla.\left(\lambda_e\nabla\langle T\rangle\right) + \rho_r X\Delta H\frac{\partial\alpha}{\partial T}$$

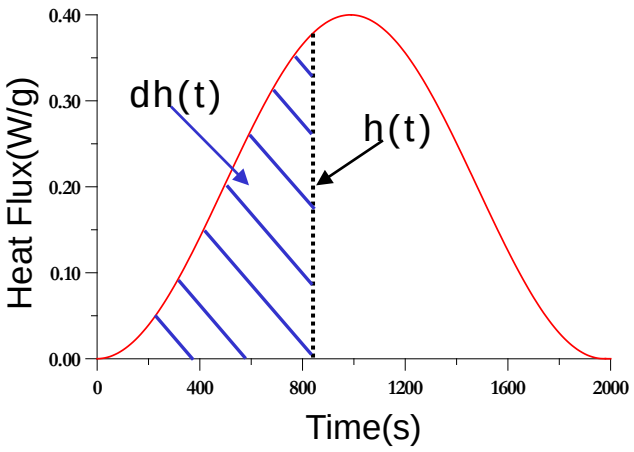
$$\frac{\partial\alpha}{\partial t} = f(\alpha, T)$$

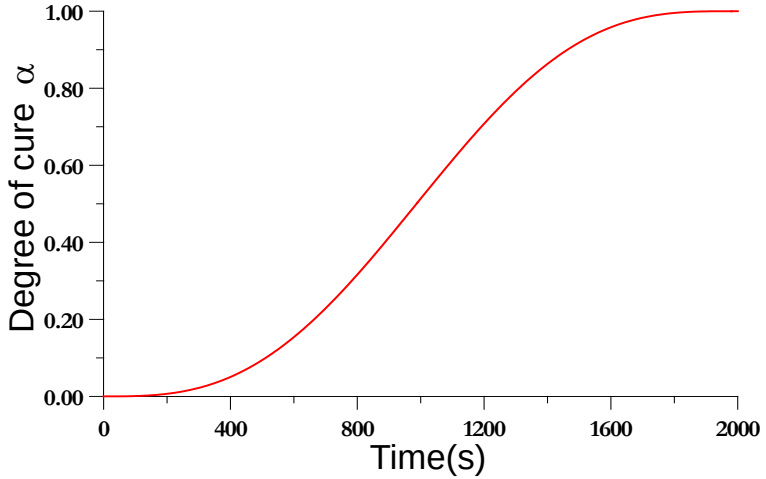
Equation highly coupled if ΔH is large or if the rate ($\partial\alpha/\partial t$) is important

X : Resin mass fraction
ΔH : Crosslinking enthalpy (J.kg^{-1})
dα/dt : Conversion rate (s^{-1})
α : Conversion degree



Conversion rate and conversion degree





Total enthalpy

$$\Delta H = \int \phi(t) dt$$

Conversion degree

$$\alpha(t) = \int_0^{t_{max}} \frac{\partial \alpha}{\partial t} dt = \frac{dh(t)}{\Delta H}$$

$$0 \le \alpha \le 1$$

Conversion rate

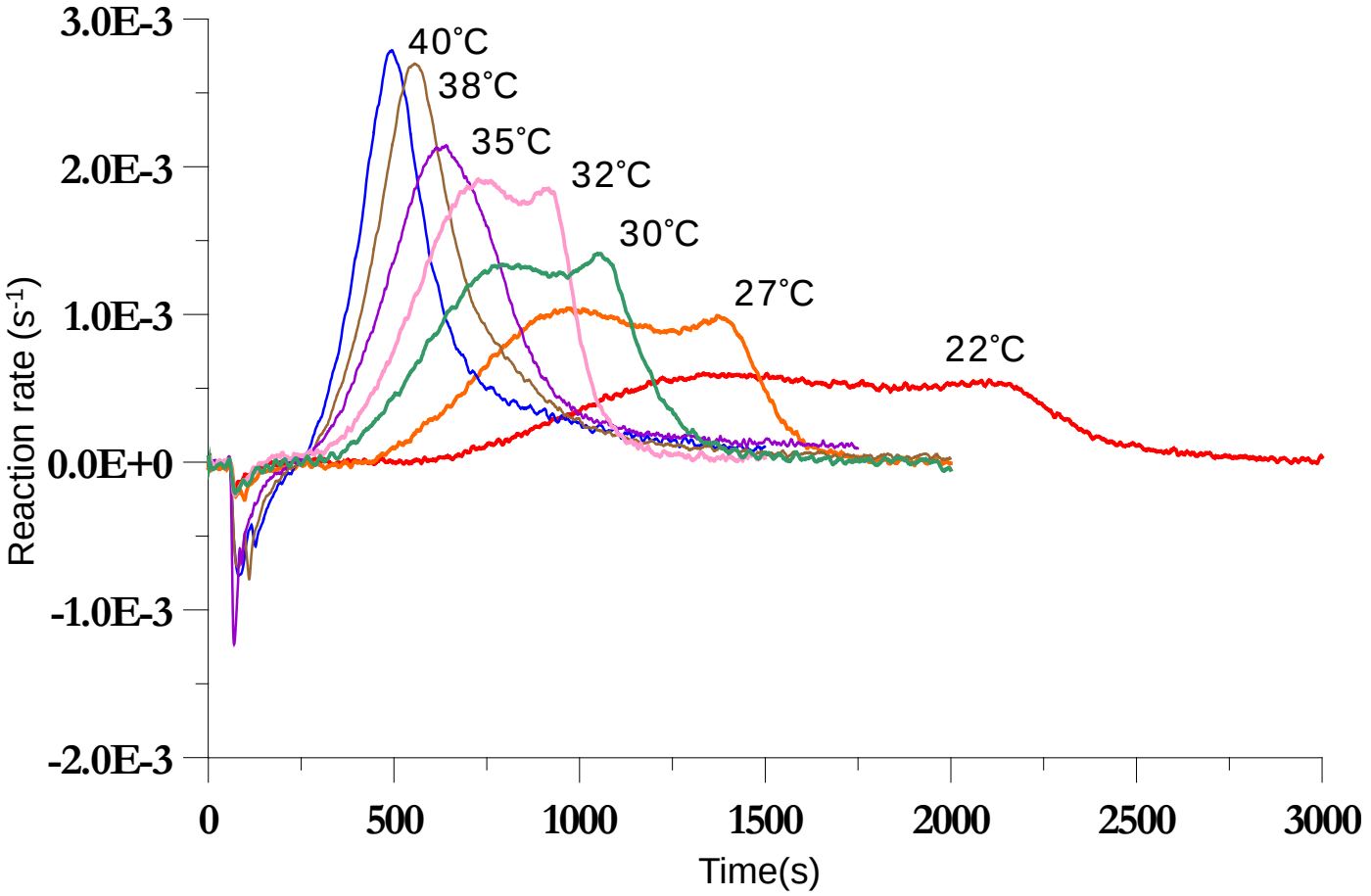
$$\frac{\partial \alpha}{\partial t} = \frac{h(t)}{\Delta H}$$

Example of impact of temperature on reaction rate

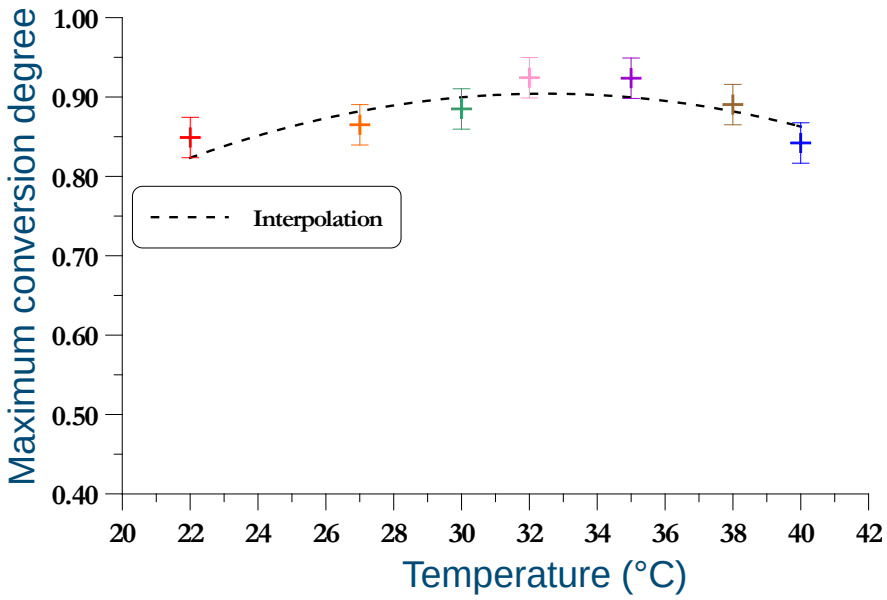
POLYTECH NANTES

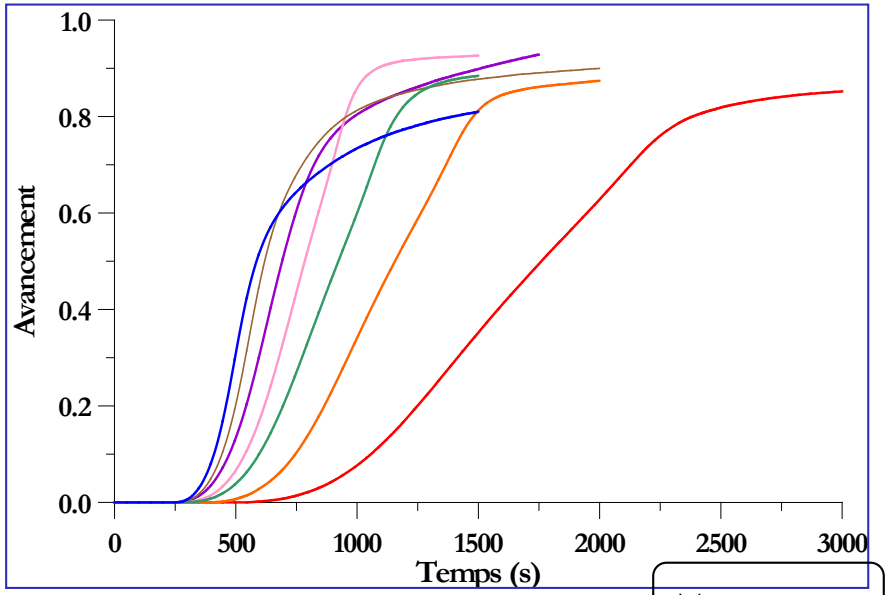
Isothermal experiments carried out for a polyester resin

Explanation of unexpected phenomenon??



Example of impact of temperature on reaction rate



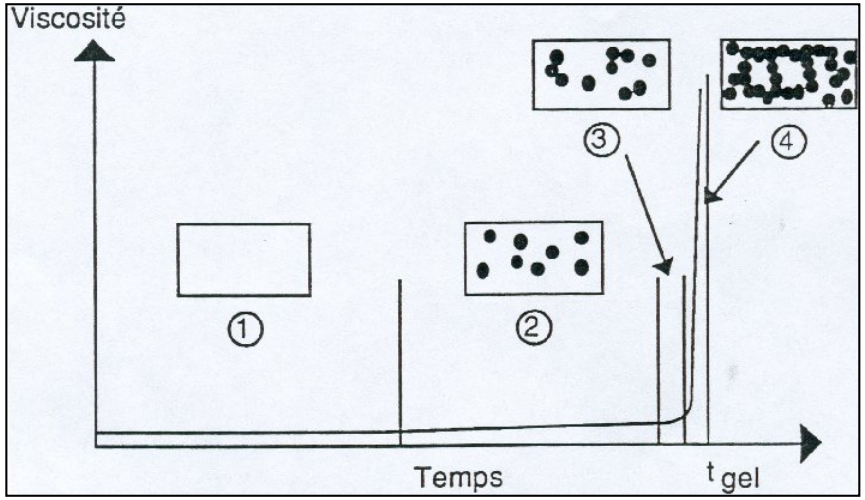


Example of impact of temperature on reaction rate

The **pre-polymer (UP)** consists initially of short and unsaturated macromolecular chains placed in solution in a monomer which is, generally, **styrene (St)**.

Catalyst system :

- Initiator : organic peroxide
- Catalyst: cobalt octoate



Two main constituents

Prepolymer (UP)

Monomer Styrene (St)

Two main reaction mecanisms

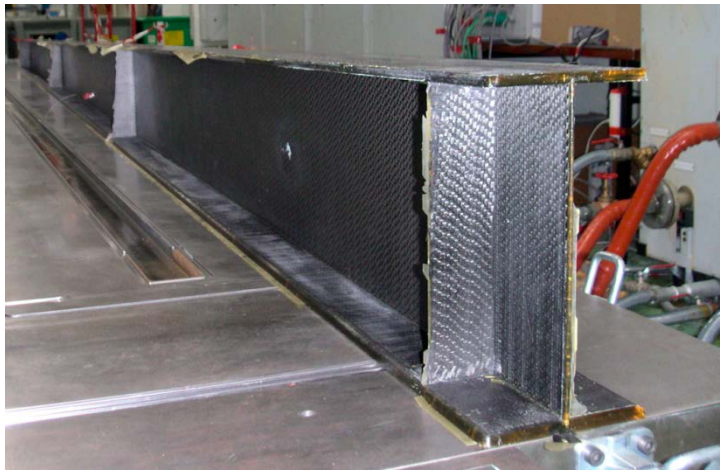
Copolymerization Up-St

Homopolymerization St-St

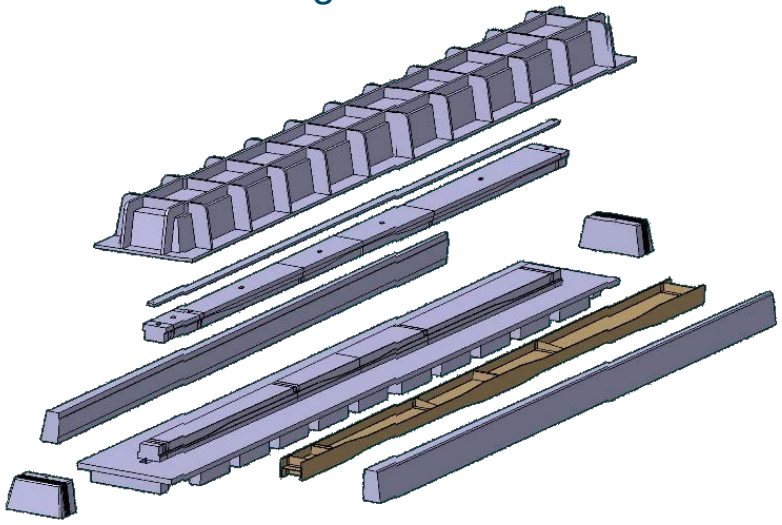
Reaction is exothermic
Creation of 3D network → shrinkage

VIII. Heat transfer in the mould

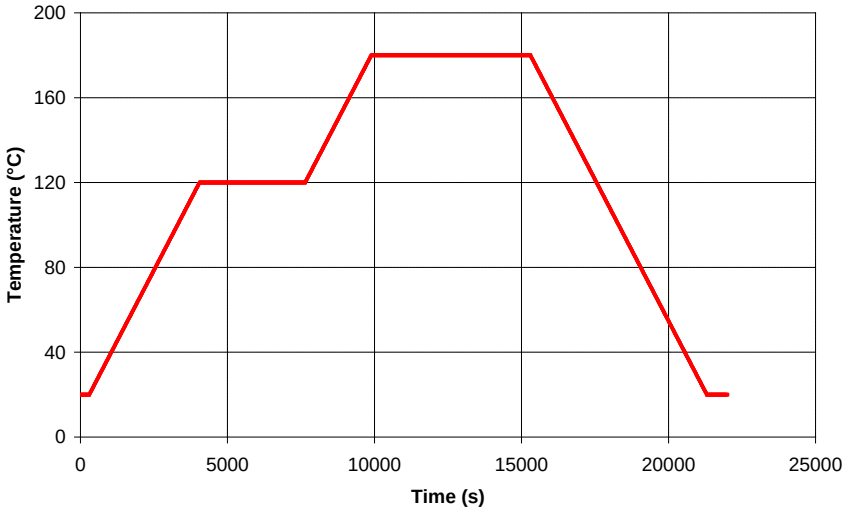
Heat system design



Technical drawing of the mold



Objective: design the heat system of the mold so as to reach the following temperature cycle in the composite part

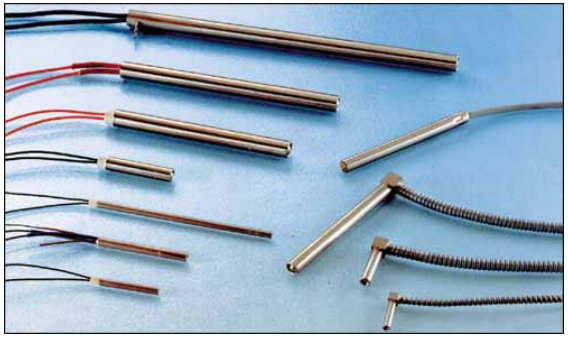


Pictures of the mold

Material	Mass (kg)
Aluminum	3050
Steel	4700

Required power?

Heat supply media



Avantages / Drawbacks?

POLYTECH NANTES

ATMOSPHERIQUE : HUILE 180°C, 250°C et 300°C MAXI

Vulcatherm® CHAUD / FROID 10803

SUPERPOSITION DE FLUIDE

Atmosphérique en circuit fermé

Haute performance - Respect du fluide Précis - Robuste

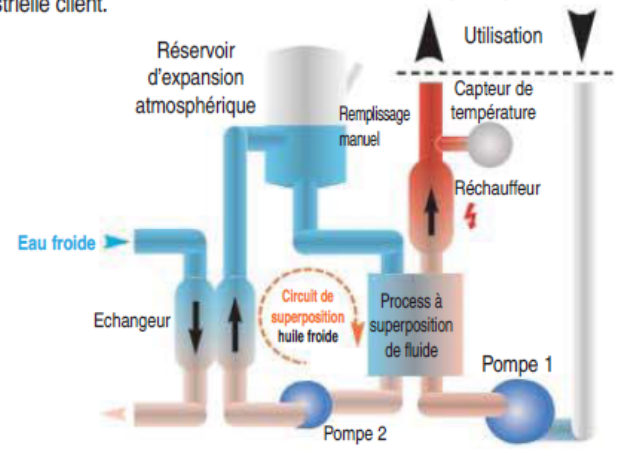
Chauffer, refroidir et **réguler** une boucle fermée de fluide caloporteur (**huile minérale ou synthétique jusqu'à 300°C**).
L'huile chaude du circuit d'utilisation est refroidie dans un échangeur alimenté par le réseau d'eau industrielle client.

Applications :
- process industriels à haute température et basse pression
- Réacteur
- Plateaux de presse
- Moules composites ...

Caractéristiques :
- Utilisation courante :
  Huile minérale ISO32 jusqu'à 250°C
  Huile synthétique jusqu'à 350°C
- Remplissage manuel
- Alimentation électrique 400VAC Tri + T

Constitution :
- 1 réchauffeur électrique instrumenté
- 1 échangeur (refroidisseur)
- 1 réservoir d'expansion atmosphérique
- 2 pompes
- 1 armoire électrique intégrée avec système de gestion centralisée (**SGC V2**)
- capteurs de mesure et de sécurité
- ensemble carrossé peint et équipé de roulettes

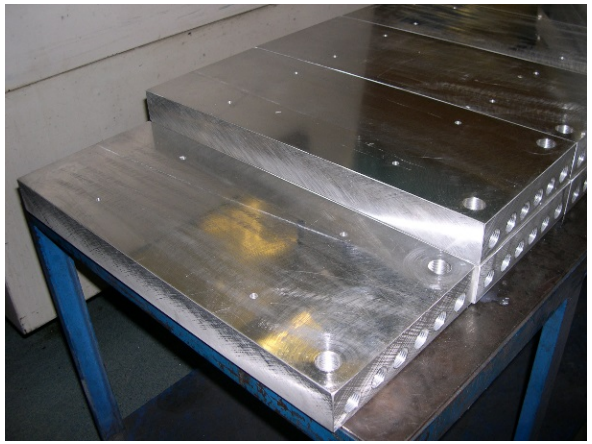
Schéma de principe



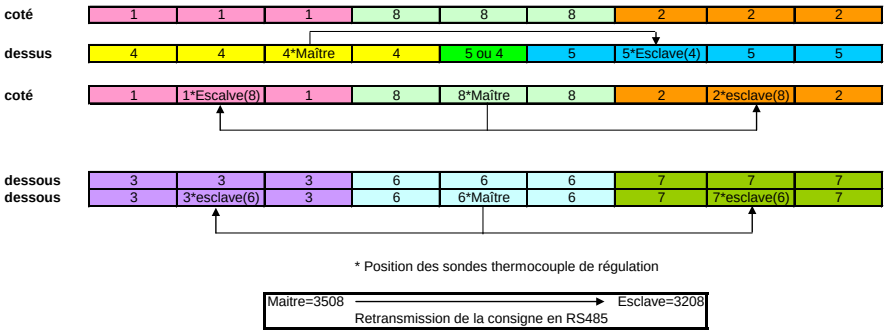
VULCATHERM®	CHAUD / FROID à superposition de fluide								
Pression maxi	10 bar								
Δt	205°C Maxi						240°C Maxi		
Chauffage d'huile jusqu'à	250°C						300°C		
Puis. Chaud +5/-10% (kW)	Puis. Froid (kW)	Débit Nom. (m³/h)	Δp Maxi (bar)	Dimensions L x H x P (mm)	REF.		Δp Maxi (bar)	Dimensions L x H x P (mm)	REF.
7	14	1,05	2,6	400 x 780 x 860	10803-07				-
10	20	1,5	3,7	400 x 780 x 860	10803-11		3,3	500 x 1320 x 950	10803-12
14	28	2,1	3	500 x 1320 x 950	10803-15		3,1	500 x 1320 x 950	10803-16
20	40	3	4	500 x 1320 x 950	10803-20		3,3	500 x 1320 x 950	10803-21
30	60	4,5	3,9	600 x 1600 x 1000	10803-30		3,3	600 x 1600 x 1000	10803-31
40	80	6	3,2	600 x 1600 x 1000	10803-40		3,3	600 x 1600 x 1000	10803-41
60	120	9	3,5	600 x 1600 x 1000	10803-60		3,3	600 x 1600 x 1000	10803-61

Sur demande :
- **Puissances : 75 à 245 kW**
- **Temp. jusqu'à 350°C**
- Pompe à accouplement magnétique
- Pompe à débit plus élevé
- **Voir autres options page 144**

Definitions of heat exchangers



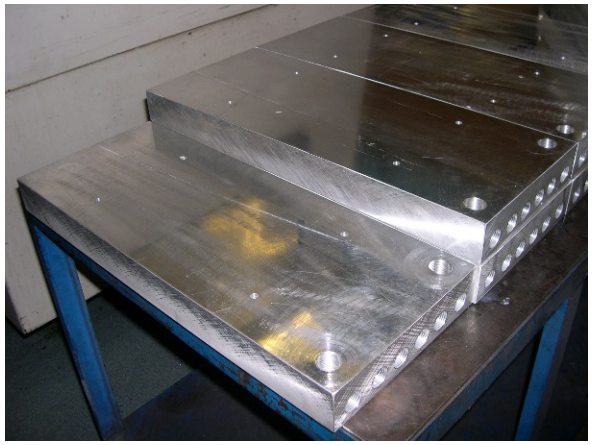
Repartition des zones de chauffe pour le demonstrateur final



45 heat exchangers (0.5m*0.2m) disposed on the mold allow the supply/evacuation of the required power

⇒ Power by platen?

Calculation of heat transfer coefficient



Use of Colburn correlation

$$Nu_D = 0.023 Pr^{1/3} Re_D^{0.8}$$

Nusselt number: $Nu = \frac{hD_h}{\lambda}$

Prandtl number: $\mathrm{Pr} = \frac{\nu Cp}{\lambda}$

Reynolds number: $\mathrm{Re} = \frac{VD_h}{\mu}$

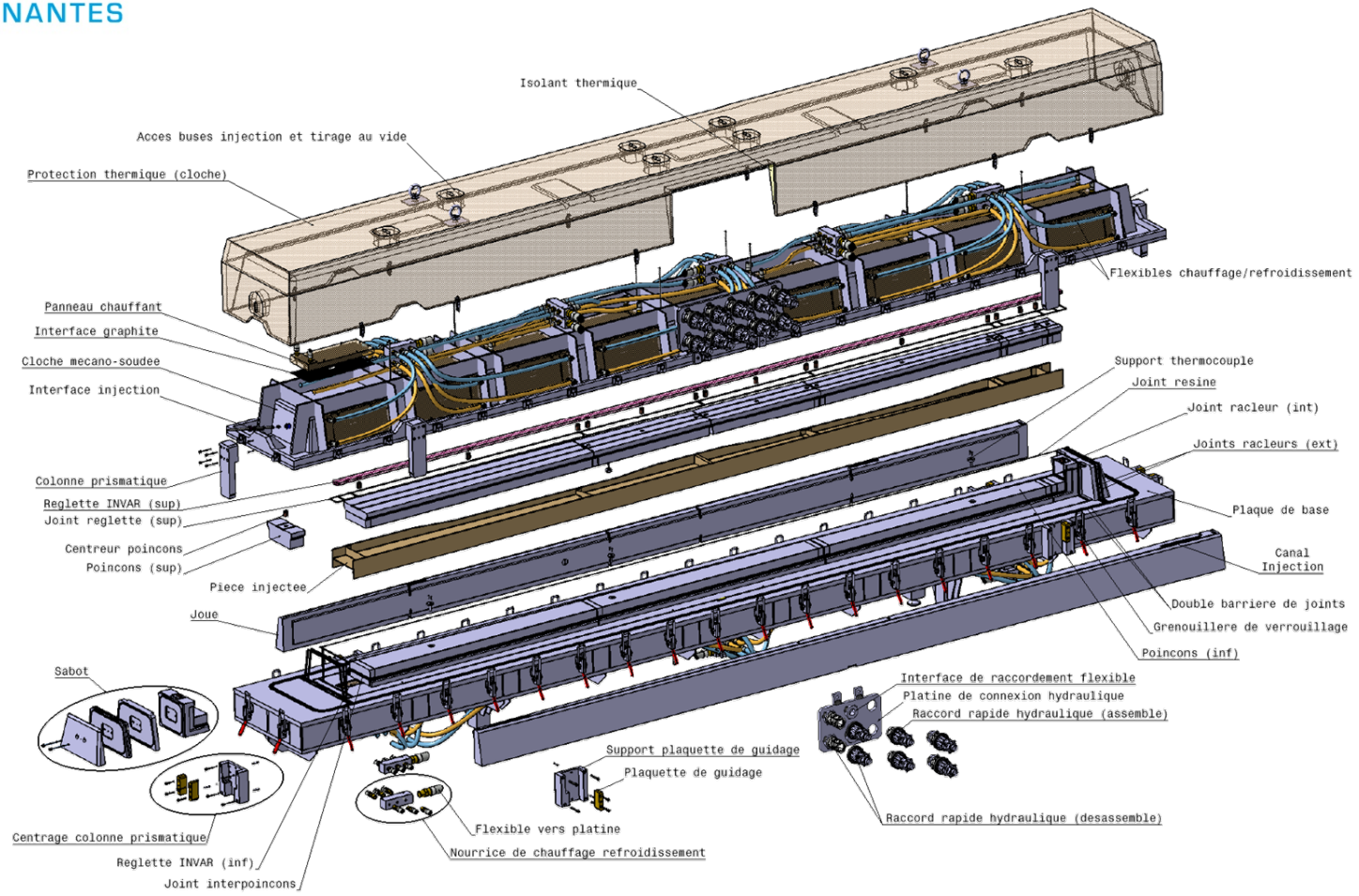
μ : kinematic viscosity (m^2s^{-1})
ν : dynamic viscosity (Pa.s)
λ : thermal conductivity (W/m.K)

Properties of the coolant fluid :

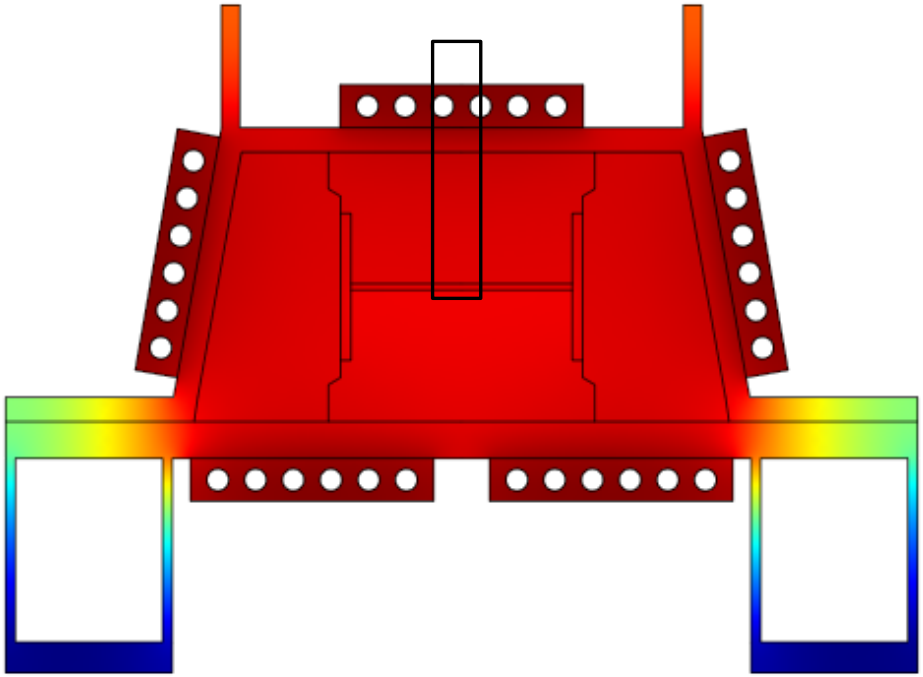
$$\begin{cases} \rho = 918\, kg.m^{-3} \\ Cp = 2160\, J.kg^{-1}K^{-1} \\ \mu = 1{,}02.10^{-6}\, m^2 s^{-1} \\ \lambda = 0{,}114\, Wm^{-1}K^{-1} \end{cases}$$

h=??

CAD of the mold



Quid de la simulation thermique?



Calculation of the temperature of the fluid in the cooling channel

Modeling and simulation of heat transfer

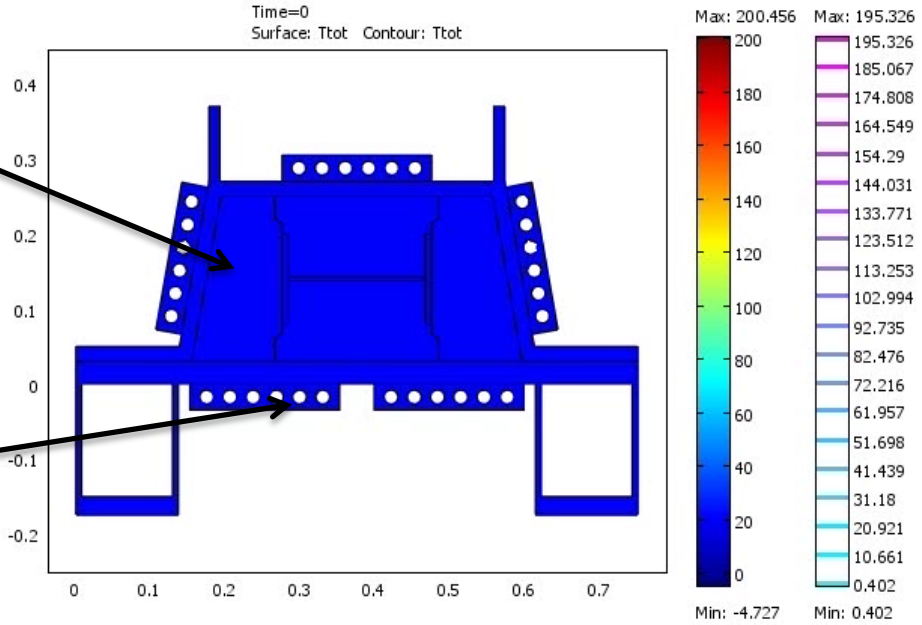
Transfers by conduction in the tool

$$\rho Cp \frac{\partial T}{\partial t} = \nabla.(\lambda \nabla T)$$

Boundary condition of the third kind in the channels

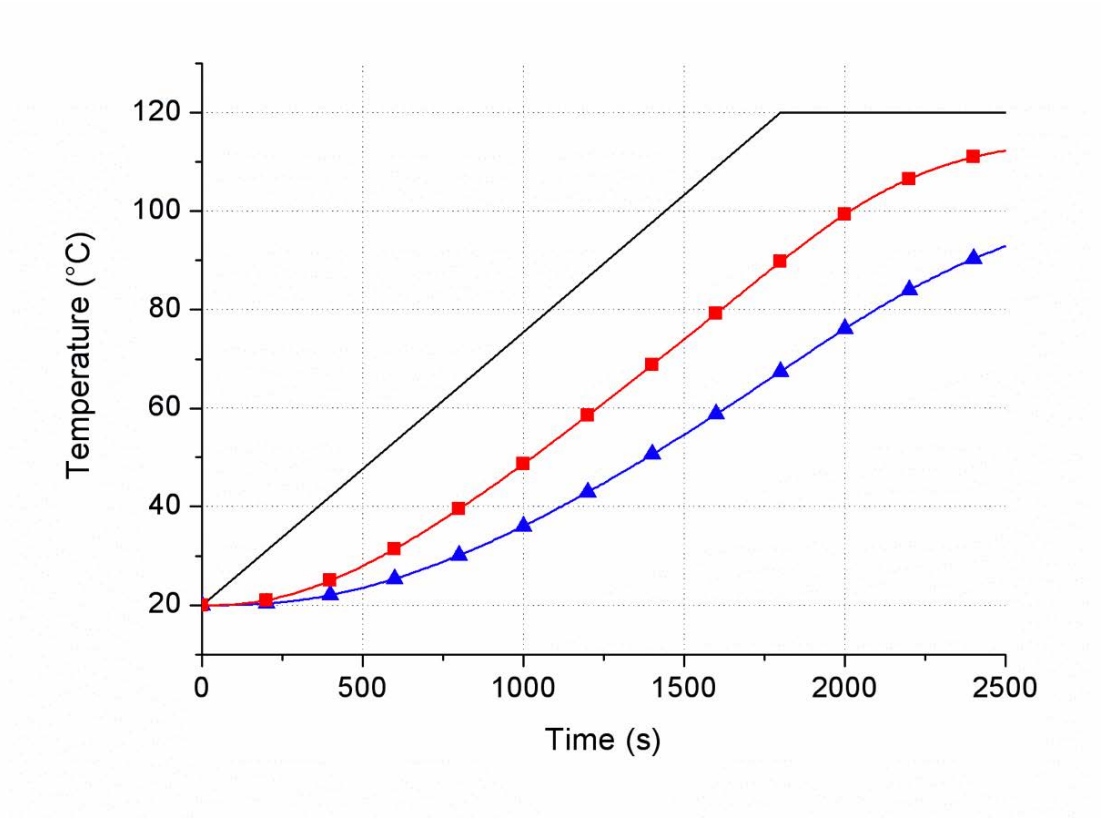
$$-\lambda \left.\frac{\partial T}{\partial n}\right|_{\Gamma} = h_{\infty}(T_{\infty} - T)$$

Parameter that must be estimated



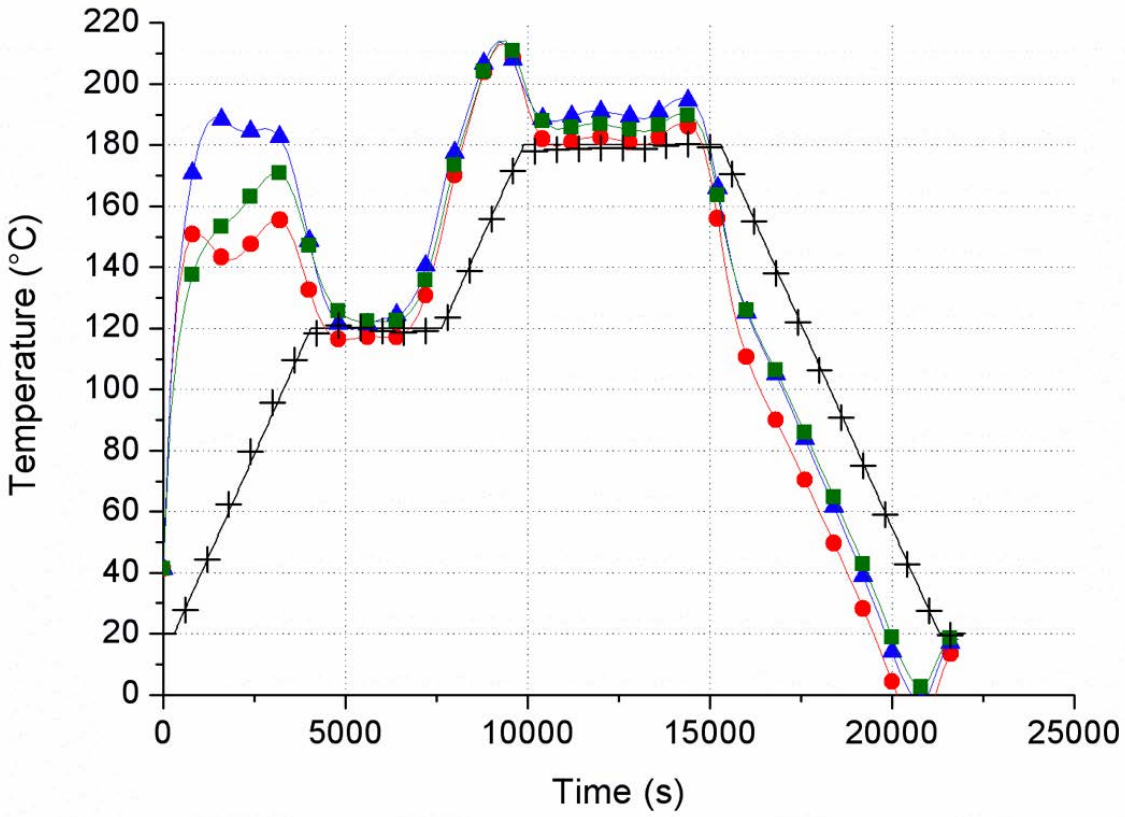
Uniformity of the temperature field in the part when the same setpoint temperature is used for all heat exchangers → **one can use the same setpoint for all platens**

Influence of Thermal Conctact Resistance



Influence of TCR on temperature in the composite part (▬ set point temperature, ■ Part temperature with perfect contact, ▲ temperature with TCR)

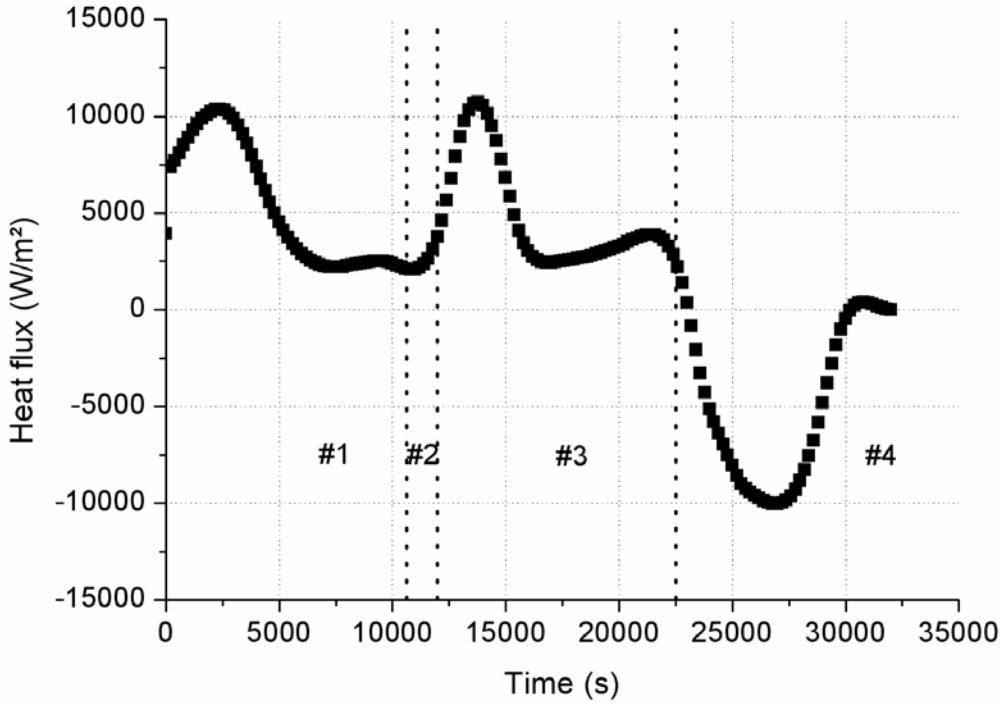
Determination of the optimal setpoint temperature



Temperature in the composite part (▬ desired, ✚ estimated) and fluid temperatures inside the heated platens (● T_{fluid_left}, ▲ T_{fluid_up}, ■ T_{fluid_bottom})

POLYTECH NANTES

Heat flux cycle to impose in the heat exchangers to reach the desired temperature cycle within the composite part.



Non intuitive → need to use an optimization method