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Infiltration behaviour of liquids over fibres or woven

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Abstract. The high porosity of fabrics and fibres have hindered the study of the interaction between fluids and those kind of materials. In order to understand penetration mechanisms of polymeric matrices or woven sealing, some properties such as wettability or capillarity must be analysed. The fluid speed through some woven could be compared with metallic meshes in those is easy to determine pores size. In this work it is tried to solve these problems from a theoretical point of view by using hydrostatic laws and capillarity effect.

1. Introduction

Capillarity phenomena together with the permeability to air and steam water are the most important factors in all types of porous materials including fibres, especially regarding natural materials. For example, in the textile industry it is necessary that fabrics allow the evacuation of hot air in order to permit the perspiration of the skin. In this way more comfortable clothes are obtained. This can be achieved by using tighter fibres with a greater number of yarns. Another example of natural material is cork. There are some studies of cork used as a reinforcement of adhesives to improve the impact resistance, the porosity of the cork allows the adhesive to get inside the pores [1], although the material has a low surface energy [2].

In other industries, such as construction, capillarity in concrete is an important drawback because it could produce humidity problems in buildings and, as a consequence, deterioration of the construction [3]. In the automotive industry metallic filters for air and liquids like oil are used. The efficiency on these filters will depend on capillary size and interconnection between pores.

Nowadays, the applications of polymeric composite materials reinforced with fibres like glass, carbon, aramid, etc. are very numerous and continue growing. These materials can be applied in different industries such as aviation, aerospace, sports or automotive, and in conclusion, in all those applications where weight reduction is mandatory without compromising mechanical properties [4,5].

When the fabric spaces are large enough and had the right interconnections to be invaded by fluid molecules, several processes take place. Consequently, according to the imbalance among different atoms can be produced capillarity processes [6-8].

The models by which a liquid is keeping in contact with a porous material independent of its nature has already been studied [9], where some important concepts are defined. For example the ability of some materials to absorption of liquid as hygroscopicity, that is influenced by combination effect of environment conditions. Besides, the nature, physical dimensions and form of the pores affect to vapour amount absorbed.

When a liquid and a solid are in surface contact state the liquid can be absorbed by the solid by means of capillarity. The capacity takes place because of the interactions among the solid, liquid and gas phases. Through the pores, liquid movements are produced by suction phenomena, so it can be considered that the penetration and speed of the process depends on the nature, geometry and roughness of the fibers in this case.

By different equations and laws as Young's equation and Jurin law, the relationships between some measurable concepts are defined: contact angles (θ), the liquid height (h) as a result of pressure variation [10,11]. In accordance with this, the necessary pressure (ΔP), to move the liquid across a capillary of radius r, is obtained by the capillary effect and hydrostatic pressure of the liquid used to measure, according to equation 1 (figure 1). It is very easy to realize that an external pressure (as the one produced in a hot plate press or autoclave) will increase this pressure and therefore the hydrostatic term can be considered negligible.

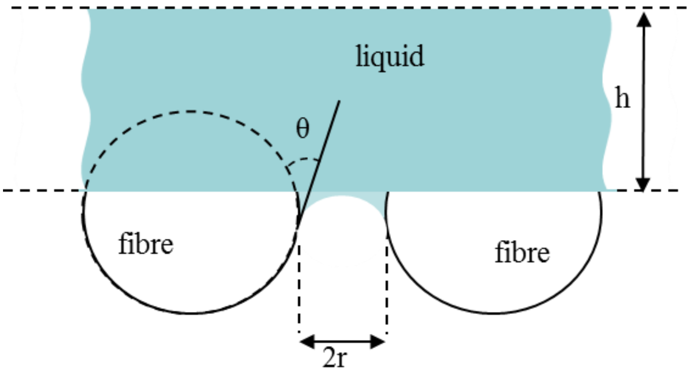

Figure 1. Scheme of liquid infiltration between two fibres (own).

$$\Delta P = \frac{2\gamma_{LG} cos\theta}{r} + h\rho g \quad (1)$$

where: γ_{LG} = liquid surface tension (N/m).

There is an inversely proportion between the contact angle on the fibres or the entry pressure of the liquid with the wettability (Kw), when one increases the other decreases. Besides, the wettability depends on the material type. As well as if Poiseuille's law is considered, speed and pressure are connected by equation 1. In the case of a laminar flow is possible to define the flow rate Q (m^3/s) and fluid speed V (m/s) by equations (2) and (3) where other parameters, as the fluid viscosity μ (Pa.s) and woven thickness L (m), are required.

$$Q = \frac{\pi r^4 \Delta P}{8\mu L} \quad (2)$$

$$V = \frac{r^2 \Delta P}{8\mu L} \quad (3)$$

By Darcy's equation the permeability can be evaluated according to equation (4), that is defined in this case as an ability of the woven fibres because it depends on its interconnected pores.

$$Q = \frac{KA\Delta P}{\mu L} \quad (4)$$

where: A = total area of wet woven

The pore section is not really constant and the length is larger. The uneven shape of the pores produces a length increment and there are also changes in the capillary section. These different sections require higher pressure to make the liquid pass across it, for this reason the measure is more difficult. The measure is easier on metallic meshes with a defined mesh size than woven fibres [12]. Porosity parameters are shown in table 1 and figure 2. The average radius value (r) has been calculated taking into account the mesh dimensions and the capillary diagonal. Thickness (L) was measured with all four layers together. Wet area (A) and pores number that water drop covers (n) were measured during the experiment.

Table 1. Metallic mesh with different pore size [12].

Mesh	*r* (mm)	*L* (mm)	*A* (cm^2)	Pores Number
150	0.181	3.88	15.21	243
110	0.133	2.28	23.80	690
90	0.108	1.60	17.37	920

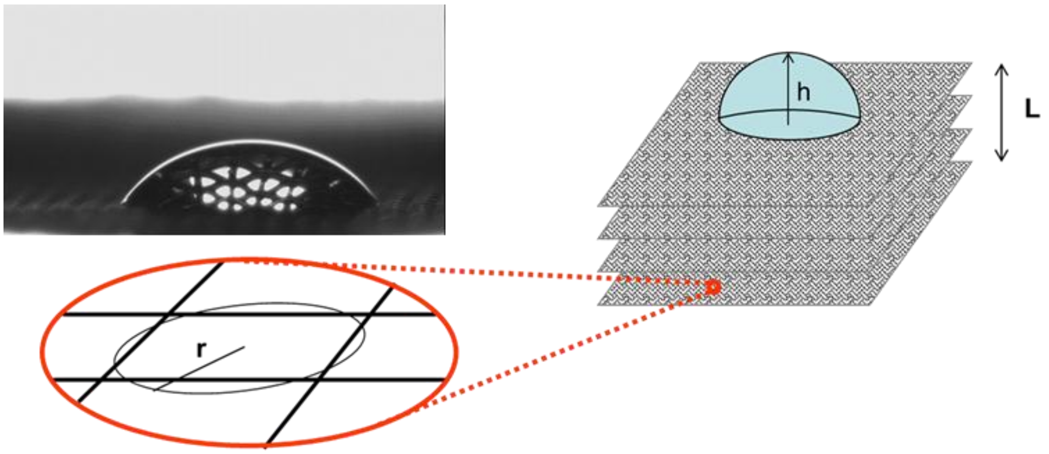

Figure 2. Mesh porosity parameters (own).

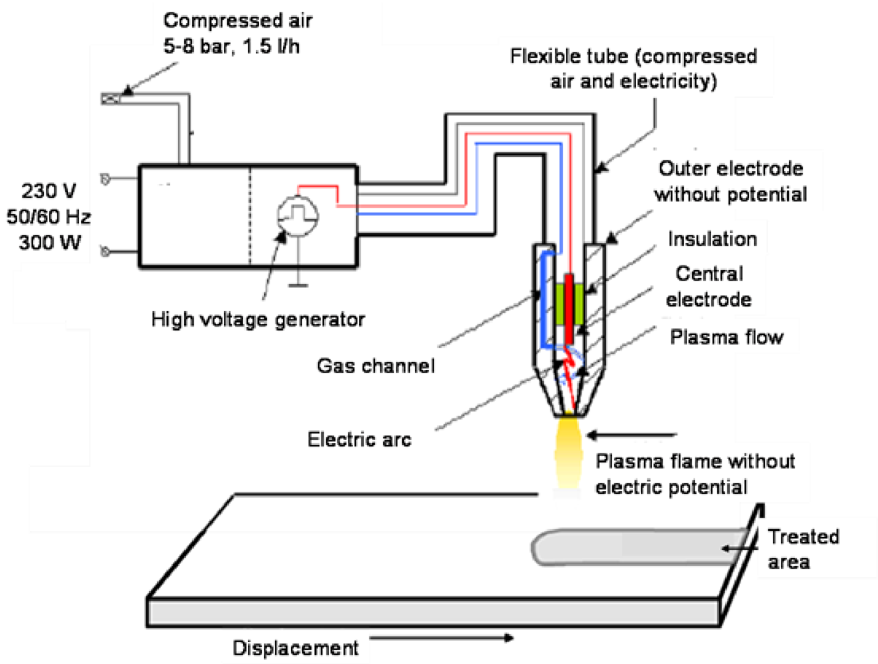

Figure 3. Atmospheric plasma torch treatment device (own).

When a cold plasma treatment is applied, ions and electrons are reorganized and act on the surface materials modifying its chemical and physical nature without affecting volume properties. Atmospheric Pressure Plasma Torch (APPT) mainly effects are cleaning, pollutants decomposition, grafting and polar groups, as -OH, -COOH, -CO and -NH, cause the activation of the surface. Therefore, surface energy increases in a significantly way and it is traduced in polymers adhesion properties improvement [13,14]. As seen in figure 3 the torch is coupled on a table with displacement to control the rate, the torch can also be moved, this way the sample distance is modified. Both parameters need to be optimized to obtain an optimal treatment.

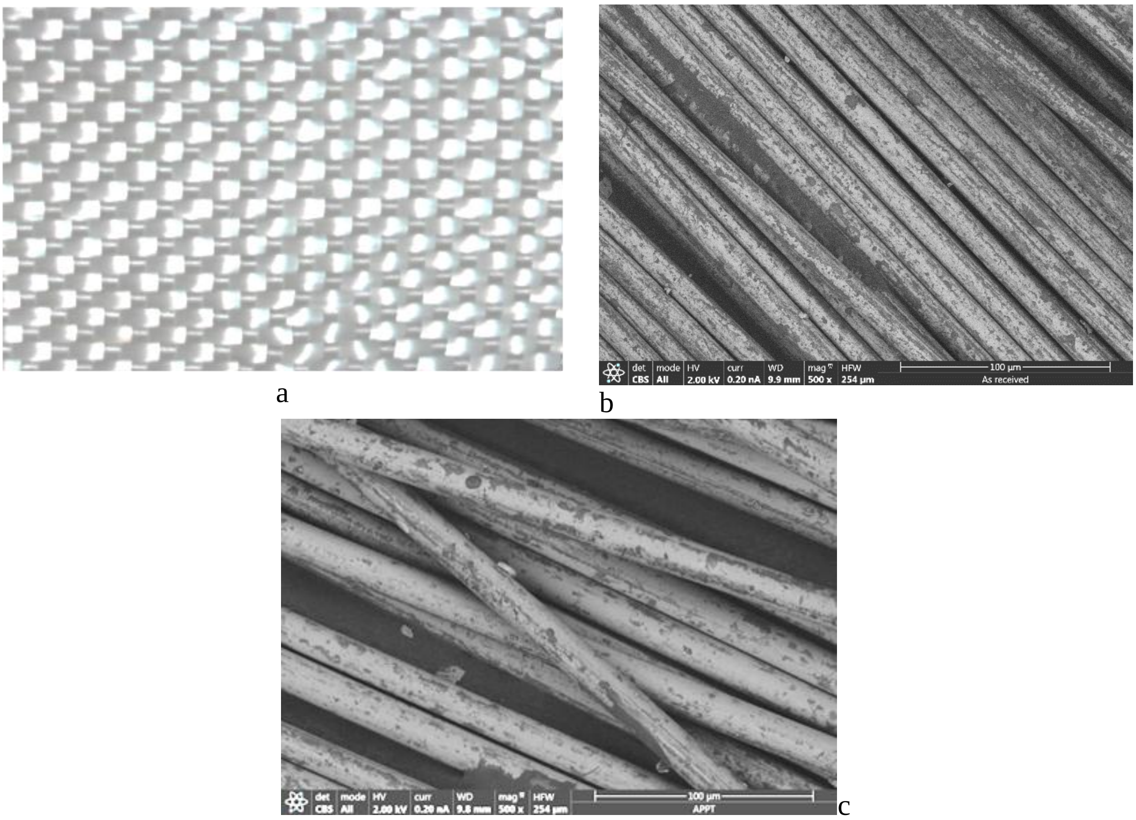

Figure 4. (a) Glass fibre woven picture; (b) Micrograph of untreated Glass fibre; (c) Micrograph of Glass fibre treated with APPT.

2. Experimental study

By measuring contact angles and flow rate calculation, as it was done with metallic meshes, a glass fibre woven with an unknown porosity (Vetrotex-P-204-2400 Tex) provided by Saint-Gobain (Aachen, Germany) was studied (figures 4(a) and 4(b). The process was then carried out on the glass fibre woven which was treated with atmospheric plasma torch (APPT) to raise the wettability (figure 4(c)). The woven was treated with an atmospheric pressure plasma torch (APPT) device with operating conditions 50/60 Hz, 230 V and 16 A (PLASMATREAT GmbH, mod. FG 3001, Steinhagen, Germany). The optimized parameters of the treatment are distance between torch nozzle and woven sample (8 mm) and speed of sample under the plasma flow (0.08 m/s).

Optical goniometer OCA manufactured by Dataphysics of Instruments GmbH (Filderstadt, Germany) was used to calculate the contact angles and drop penetration into the woven fibre. This device has a movie mode which is used to analyse the water drop penetration through several filters. This mode allows determine the liquid flow rate as a function of time. The values obtained for the fibres are compared with those obtained for metallic mesh [12]. So is possible to know the woven fibre capillarity.

3. Results and discussion

The study of the effect of APPT treatment on glass is already carried out in other works [15]. Due to the high intrinsic surface energy of glass the effect of APPT is only cleaning but not activation. In this work the glass fibre woven is covered with a layer of thermoplastic material, as all commercial fabrics have, so plasma treatment acts on the thermoplastic layer instead of directly on glass. For this reason contact angles measured with polar liquids (distilled water and glycerol) decreases and those measured with a dispersive liquid (diiodomethane) increases after treatment, as it is shown in table 2. According to Encinas *et al* [13], APPT treatment produces a surface energy increment and, as a result, a wettability increment.

Table 2. Contact angles (º) on untreated and APPT treated woven glass fibres using different test liquids.

Woven Fibres	Distilled Water (º)	Diiodomethane (º)	Glycerol (º)
GF	112	28	118.0
GF + APPT	42	52	55.3

Figure 5 shows filtration rates of glycerol through untreated and APPT treated woven glass fibres. Results are compared with those obtained with water through metallic meshes. The liquids were changed for their different viscosities, searching in this way the same effect on the woven that on the mesh, and therefore the slopes of the corresponding curves coincide.

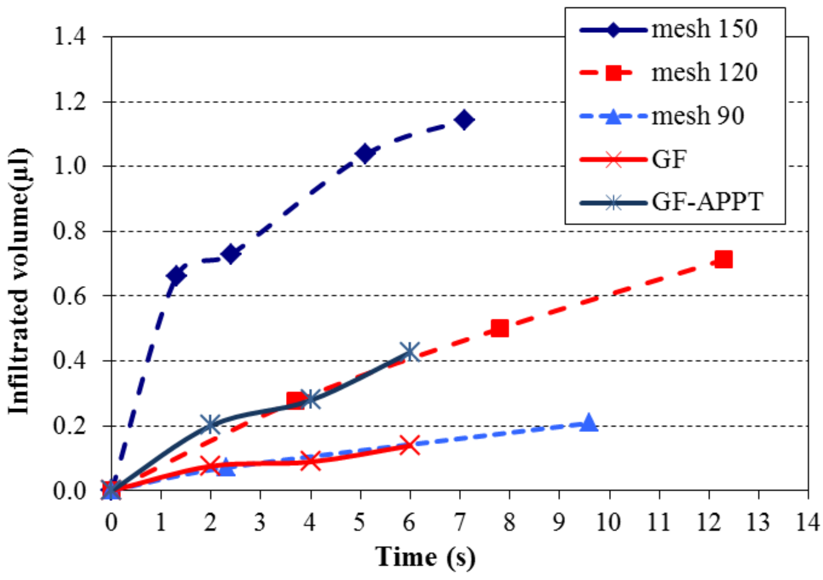

Figure 5. Infiltrated drop volume variation versus time.

Once is verified that the infiltrated drop volume through metallic meshes is similar to the one obtained on glass fibre woven, all infiltration parameters can be calculated with equations from (1) to (4). If surface tension, viscosity and density of distilled water is known (γ_{LG} = 72.75 mJ/m^2, μ= 0.001 Pa.s y ρ = 997.13 kg/m^3 a 25 ºC) infiltration parameters of the water through metallic meshes can be obtained. Regarding pressure, the hydrostatic component is negligible due to the small size of the drop. Table 3 shows contact angle measurements using water as test liquid on metallic meshes and other infiltration parameters.

Table 3. Infiltration parameters of water obtain on metallic meshes.

Material	Contact Angle (º)	Flow Rate (μl/s)	Pressure (Pa)	Speed (mm/s)	Permeability ($m^2 x10^{-3}$)
Mesh 150 μm	80	0.161	1483	1565	2.77
Mesh 120 μm	120	0.060	1114	1080	0.56
Mesh 90 μm	110	0.022	659	600	0.31

Glycerol infiltration flow on untreated woven glass fibres is the same as the one obtained for 90 μm metallic mesh and glycerol infiltration flow on APPT treated woven glass fibres is very similar to 120 μm metallic mesh. These results could be explained by the effect of the APPT, which increases wettability and therefore flow rate is higher (as in a bigger metallic mesh). Accordingly, the rest of the glycerol infiltration parameters can be obtained if surface tension, viscosity and density are known (γ_{LG} = 63.10 mJ/m^2, μ= 1.5 Pa.s and ρ =1261 kg/m^3) and woven thickness is 0.91 mm. Results are shown in table 4.

Table 4. Infiltration parameters of glycerol on glass fibre woven obtain with and without APPT treatment.

Material	Total Area (cm^2)	Contact angle (º)	Flow rate (μl/s)	Pressure (kPa)	Speed (mm/s)	Permeability ($m^2 x10^{-10}$)
Glass woven	0.75	28.1	0.023	562	0.30	7.45
Glass woven +APPT	4.20	52.2	0.071	667	0.16	3.46

4. Conclusions

The obtained data allow to know the theoretical parameters of the woven fibres.

If drop size and flow rate are known is easy to determine the theoretical parameters that define porous materials, this are porosity, fluid pressure, wettability and permeability values.

In this study has been proved that the more wettability the more flow rate of liquids through glass fibre woven. This wettability increment is due to the effect of APPT treatment which makes that the glass fabric behaviour could be resembled to the one obtained for metallic meshes with bigger pore size.

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