The Imbibition Process of Terylene and Polypropylene Fabrics

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\textbf{Abstract.} Capillary imbibitions were of practical importance in many industrial processes such as textile, ceramic, and pharmaceutical industries. In earlier studies, it had been found that the resistivity of terylene or polypropylene fabrics decreased via water penetration, but little work has been done on imbibitions process which is essential to reveal the interrelation between water penetration and conductivity of terylene or polypropylene fabrics. The study was inspired by the requirement to investigate more details about these interrelations. The results showed that drop spreading existed in imbibitions experiments when the hydrophobic fabrics were contacted with water. Five different physical stages occurred successively during the imbibitions behavior experiments, namely solid-liquid contact(A), imbibition(B), steady balance(C), solid-liquid separation(D) and evaporation of external liquids(E) stages. The phase of solid-liquid contact reflects the equilibrium relationship between the wetting tension and the buoyancy of the liquid. The resistivity of polypropylene fibrous decreased to $2.4 \times 10^5 \Omega \cdot \text{cm}$ when WHC was 0.01Lm-2, thus would be enough to meet a demand or requirement for collectors. The discharge current by polypropylene collection electrode was 5~20 percent higher than that by FRP. The spontaneous immersion for water into hydrophobic fabric collectors would be of practical importance for the purpose of uniform water film distribution via capillary flow, thus would allow lower water addition rate and non-interrupted operation for industrial use.

\textbf{Introduction}

It is well known that capillary imbibition is of practical importance in many industrial processes such as textile, ceramic, and pharmaceutical industries\textsuperscript{[1-3]}. During the past 20 years, a great deal of knowledge regarding capillary imbibitions and spreading of droplets mechanisms at the pore scale have been acquired\textsuperscript{[4-9]}, but the imbibitions process aspects of the subjects do not appear to have received much attention. Moreover, wet ESPs are good options for effective control of fine particles to keep the stack opacity\textsuperscript{[10]}. In agreement with some authors, ryton, and felted-propylene collection electrodes exhibited excellent particulate exceeding those of steel plates as measured in several experiments\textsuperscript{[11-13]}. Recently, it has been proved that the collection efficiencies by single terylene and polypropylene fabrics were higher than those by fiberglass reinforced plastics (FRP) under certain conditions in some of our previous works\textsuperscript{[14]}. In other words, terylene or polypropylene collection electrode was consistent with the behavior of conventional FRP using thimbleful of water passing over the insulated surface. These hydrophobic fabrics are possessed of some properties such as significant resistance to acid and alkaline corrosion, the higher thermal stability and the reasonable costs as reported\textsuperscript{[15]}. However, terylene and polypropylene fabrics are hydrophobic and insulated before washing water penetrating them via capillary flow, and earlier studies focused on the kinetics of the imbibitions for hydrophilic fabrics contacted with water have shown that two simultaneous imbibitions processes of the fabric: (i) a volume imbibitions inside the strands of yarn and (ii) a surface rise\textsuperscript{[16]}. In earlier studies, it had been found that the volume resistivity of terylene or polypropylene fabrics were controlled by the water addition rate, but little work has been done on
imbibitions process of water capillary penetration for terylene or polypropylene hydrophobic fabrics which is essential to reveal the interrelation between water penetration and conductivity of terylene or polypropylene fabrics.

Among the experimental techniques, two methods are the most commonly utilized: height-time method\(^{[17]}\) and weight-time method\(^{[18]}\). In both cases, the experimental results have been analyzed using Washburn’s equation\(^{[19]}\). In the first stage of the capillary rise, namely the height \(h\) of the liquid front is smaller than the equilibrium height \(h^*\), and the capillary time \(t\) is smaller than the equilibrium time \(t^*\). Gravity can be neglected, and the Washburn law is dimensionally applicable (\(m \sim t^{1/2}\)).

Weight-time method was proposed in order to avoid the measurement error of height-time method. Washburn’s equation in term of weight can be derived:

\[
2w = at
\]

\[
a = \frac{(\varepsilon \rho x_1 x_2 r)^2 \Delta P}{4 \eta}
\]

Where \(w\) is the weight of a liquid that penetrates into porous media, \(a\) is a constant related to the surface tension and viscosity of the liquid, as well as to the average radius of the capillaries. Where \(\varepsilon\) is the porosity of the layer, \(x_1\) and \(x_2\) the dimensions of the lower base of the layer, \(\rho\) the density of the liquid, \(r\) the radius of the capillaries, \(\eta\) the viscosity of the liquid, \(\Delta P\) the difference of pressure across the liquid-vapor interface, and \(t\) the penetration time.

In some previous papers, some studies indicated that the experimental increase of weight could also be written as \(^{[17, 20]}\)

\[
w_{\text{exp}} = w_{\text{cont}} + w_{\text{imb}} - w_{\text{evap}}
\]

Where \(w_{\text{exp}}\) is the weight recorded by a digital balance, \(w_{\text{cont}}\) is the increase caused by the liquid surface tension when the solid is put in contact with the free surface of the liquid, \(w_{\text{imb}}\) is the penetration of the liquid inside the porous body, and \(w_{\text{evap}}\) was the mass absorbed by fabrics via evaporation.

With regard to weight-time method, it is known that two different physical phenomena occurred simultaneously to the increase of weight for formamide into a layer of silica gel\(^{[17]}\). However, insufficient work has been done on the process of imbibitions for water into hydrophobic fabrics. Particular descriptions including the whole process for hydrophobic fabrics contacted with water were still scarce.

In this work, we have tried to find out if there is any dissimilarity existed in imbibitions experiments between hydrophobic\ hydrophilic fabrics contacted with water, and seek to reveal the interrelation between water penetration and transformation of conductivity for terylene or polypropylene collection electrode. Concretely, the total imbibitions process experiments were carried out contacted with water, the surface morphology and the contact angles, and other important factors were examined from the initial stage. The transformation of conductivity for terylene or polypropylene fabrics was illustrated at different Water Holding Capacity (WHC).

**Experimental**

**Materials**

Imbibitions process, conductivity, and contact angles experiments were carried out with two standard and untreated terylene and polypropylene fabrics named 728 and 840A, obtained from Hangzhou Hechuang Filtration Co., Ltd., China, and their characteristics are given in Table 1. The liquids used were water, ethanol absolute and desulfurizer supernatant, and their characteristics are given in Table 2. The assemblages into strands for 728 and 840A were shown by scanning electronic microscope pictures (Fig. 1). Fig.1a and 1b show that the fabric surfaces consist of serial small alveoli and
prominent portions. In fact, capillary penetration into the yarns can be characterized by an assemblage of filaments about radius \( r \) equaling 5\( \mu \)m and 15\( \mu \)m for 728 and 840A, respectively. It can be calculated that the equilibrium height \( h^* \) was 1843.6mm and 698.6mm, and the equilibrium time \( t^* \) was 2434228s and 102492s for 728 and 840A, respectively. Because the sample's height \( h \) was smaller than the equilibrium height \( h^* \), the absorbed mass \( m \) as function of time \( t \) would abide by Lucas-Washburn law. Fig.1c and 1d show that the cross sections are porous. Capillary rise experiments were performed on fabrics of width 4 cm and height \( h_0 \) ranging between 2 and 6 cm. Before measurements, the samples were dried in an oven at 100°C±5 for 1 h and then kept in a desiccators until the moment of their use. The fabrics were brought into contact with liquids and the mass was recorded as a function of time with an accuracy of 0.1 mg. All experiments were done at 25°C.

### Table 1. Characteristics of terylene and polypropylene fabrics.

| Materials     | Weight (g/m²) | Warp / Weft /10cm | Thickness (mm) | Breaking elongation(%) | Air permeability (l/m²*s) | Weave        |
|---------------|---------------|-------------------|----------------|------------------------|----------------------------|--------------|
| Terylene      | 360           | 246/310           | 0.89           | 18~35                  | 180                        | twill        |
| Polypropylene | 340           | 198/115           | 0.78           | 20~50                  | 76                         | plain        |

### Table 2. Characteristics of penetration liquids.

| Liquids                | \( \gamma \) (mN/m) | \( \eta \) (mPa·s) | \( \gamma/\eta \) (m/s) | \( \rho \) (kg/m³) |
|------------------------|---------------------|--------------------|--------------------------|----------------------|
| Water                  | 74.06               | 1.09               | 67.95                    | 998.2                |
| Ethanol Absolute       | 20.60               | 1.34               | 15.37                    | 789.45               |
| Desulfurizer Supernatant | 46.96           | 1.17               | 40.14                    | 1024                 |

Figure 1. SEM pictures of fabrics: (1a) and (1b) surfaces of 728 and 840A, (1c) and (1d) cross sections of 728 and 840A.

### Methods

The details of capillary experimental device were shown in Fig.2(a). However it should be pointed out our amelioration for the purpose of illustrating the imbibitions process well. Firstly, the up/down moving device was replaced by miniature valves and tanks for controlling the contact between the liquid surface and the fabrics, thus we can illustrate the initial contact carefully. Secondly, the thermostatic and hermetically closed chamber was taken away to study the evaporation of external liquids. Data was recorded by digital balance before contact between liquid and solid. When the liquid reached the fringes of the fabrics, the measurements of weight and time started.

Contact angles experiments were conducted on a stage (with X-Y movements) which was fixed on an optical microscope. Images, obtain with a high speed camera Fastcam-Super 10kC (Photron, Tokyo, Japan), were analyzed using image analysis software. Experiments were conducted for drop volume range of 10~70µL. The tip of pipette was positioned close to substrate to eliminate the inertia effect, when the drop was released. Each sample was untreated before contact angles experiments. The status of droplets was observed from the initial stage, as shown in Fig.2 (b). The measurements of contact radius and the height of the drop were on the basis of edge detection technique. Before measurements, the samples were dried in an oven at 70°C±5 for 2 h and then kept in
a desiccators until the moment of their use. The volume resistivity of terylene and polypropylene fabrics was measured with different washing water penetrating them via capillary flow. Physical indicators conform to the requirements of relative national standard GB1410-2006. Also, at least three experiments were performed for each type of liquids to check the reproducibility.

Results and Discussion

Contact Angle Measurement

The contact angles of a liquid on the fabrics were measured by the CCD system as shown in Fig.3. To check the consistency of the method, different volume of droplets were considered. These were found to give almost identical results for the same liquid see Fig.3. Using hypsometry method for static contact angle calculation we were able to construct the complete profile of the meniscus and to determine how it evolved with time [21-23]. A succession of such profiles is shown in Fig.3 for drop penetration into fabrics. At the zero depth of penetration, that is the position where the fabrics just makes contact with the liquid, and the contact angle can be calculated. The images enable optical evaluation of contact angle, $\theta$, of a liquid drop height, $h$, and base diameter, $d$, as follows:

$$\theta = 2 \arctan \frac{2h}{D}$$

Because the contact angles are measured from a static plate, and the droplet was disposable sampling, they are called static contact angles. The results show that the contact angles for water on 728 and 840A were 52.5° and 136.2°, respectively, and the contact angles for ethanol absolute on 728 and 840A were 41.9° and 46.5°, respectively. This phenomenon indicated that the immersion velocity of ethanol absolute into 728 and 840A was similar, but there would be significantly difference for water immersion into 728 and 840A. Kumar [22] and Xiao [23] had shown the effect of drop size during penetration into the substrate. The diffusion distance or the immersion velocity with respect to time was nearly a constant for silicone and polyvinyl alcohol water solution penetrating into glass fiber mats. However, the penetration curves for water into 728 and 840A are given in Fig.4. For bigger and smaller drop cases, the penetration velocity of 728 represented obviously higher than that of 840A. The penetration velocity for bigger droplet was apparently faster. The following rules of drop spreading for water on 728 was Hill, and the diffusion shapes were elliptical. Meanwhile, the following rules of drop spreading for water on 840A and 840A was Hill (Fitted formula: $y=Ax^6/(K^6+x^6)$; Correlation coefficient: 0.97936, 0.94117, 0.9498, 0.9998, respectively. ). Theses apparent differences strongly suggested that there were obviously dissimilarity existed in penetration experiments between hydrophobic/hydrophilic fabrics contacted with water and hydrophobic fabrics contacted with organic liquids. These results would be in accordance with the next capillary experiments and would be confirmed again in the capillary procedure. The spontaneous immersion for water into 728 and 840A collector surface would be have practical importance for the purpose of
uniform water film distribution via capillary flow, thus would allow lower water addition rate and non-interrupted operation for industrial use.

![Figure 3](image3.png)

Figure 3. (a) Use hypsometry method to measure contact angles. (b) Profiles for different droplets penetration into 840A.

![Figure 4](image4.png)

Figure 4. (a) Variation of imbibed volume with respect to time for water on the front of 840A. (b) Variation of imbibed volume with respect to time (d) for water on the front of 728.

**Solid-liquid Contact Process of Imbibitions**

In some previous papers, the weight recorded mass equal to the sum of the mass caused by the liquid surface tension and the penetration mass subtracting the evaporation mass. However, after the zero distance of contacting, that is the position where the front fiber just make contact with the liquid, the buoyancy force is not zero. The weight recorded by analytical balance should take into account the buoyant effect of penetrated liquids, especially the contact angle is bigger than 90°.

It is well known that any liquid exerts a force over any system in contact with its free surface because of its surface tension which cannot be avoided in the initial stage of the imbibitions, namely $w_{\text{cont}}$. This effect can be clearly seen in L.Labajos-Broncano’s paper [18]. Thus the weight cause by surface tension $w_{\text{cont}}$ plus the weight caused by imbibitions $w_{\text{imb}}$ equals the weight obtained through digital balance $w_{\text{exp}}$. However, there was different thing observed when the sample's fiber came into contact with water slowly as shown in Fig.5. The solid-liquid contact process can be divided into two stages. During the first stage, the weight caused by surface tension $w_{\text{cont}}$ can be clearly seen in the experiments which were marked as “A—O and A—O’”, but the second stage shows that the duration was transient before all fringes of the fabrics contacted with water. As the contact goes on, there were very obvious descend of $w_{\text{exp}}$ for both 728 and 840A fabrics which were marked as “O—A ‘and O’—A’”, and then the increases of $w_{\text{exp}}$ can be seen as described by other authors after the point A ‘and A’. As a consequence, it cannot be defined the weight cause by surface tension $w_{\text{cont}}$ as a constant parameter for terylene or polypropylene fabrics contacted with water. There may be another subentry which was superposed on the initial stages of imbibitions for the samples contacted with water as shown in our experiments. It was observed that for 728 and 840A fabrics, buoyancy increased gradually with time and the recorded mass increased initially and dropped to negative value gradually. It is evident from the Fig.5 that the buoyancy was 0.13mg and 0.32mg for 840A and 728 fabrics before the typical capillary procedure.

In conclusion, the traction tension played a major role when the fabric fiber front came into contact with water. In this state, the bending fluid produced traction tension on the contact fiber because of the wetting force of the liquid. As a result, the quality of fabric samples increased rapidly, which could be
monitored by the balance. When the fiber front of the fabric were drawn to a certain depth by wetting tension, the buoyancy increased gradually with time caused by the hydrophobicity of the fiber 840A and 728. Eventually, the buoyancy and wetting force of the liquid were balanced, and the mass and slope turned to the stable state. However, increasing the submerged volume of the fiber, the buoyancy was obviously greater than the wetting tension of the liquid, and the liquid buoyancy played gradually a major role. The trends of fabric quality increasing or declining were corresponding to each other, and the stable value was lower than the initial sample quality, those were to reach the A ’and A’’ point. Because ethanol had good wet ability on hydrophobic fiber sample, these stages were not obvious under the same conditions in other infiltration tests.

![Figure 5](image)

**Figure 5.** Variation of weight $w_{exp}$ versus time during the course of contacting between 728(a)/840A(b) and water.

**Total Process of Imbibition**

In general, the studies of capillary penetration usually focused on the hydrophilic porous medium contacting with aqueous solutions, or on the high hydrophobic fabrics contacting with organic liquids. In fact, there was some difference between hydrophilic and hydrophobic porous medium contacting with aqueous solutions which had been verified in our experiments. Total imbibitions behavior of water into 728 and 840A was observed, and Fig.6 shows the recorded mass as function of time. The recorded mass decreased progressively in the initial stage when the front fiber of fabrics contacted with water until it reached to a minimum value. Then, an instantaneous increase in the weight was observed, followed by a regular rise until a plateau value was reached which corresponded to the saturation of the samples and which depended on the sample’s height. The value of the wetting force was obtained by the difference between the maximum weight recorded at the end of the experiments and the final weight of the liquid-solid separation experiment. If the saturated sample was exposed to air, an exponential decrease was obtained from the overall view of the imbibitions procedure in Fig.6, we confirmed that five different physical stages occurred successively during the imbibitions behavior experiments, namely solid-liquid contact(A), imbibition(B), steady balance(C), solid-liquid separation(D) and evaporation of external liquids(E) stages. For the solid-liquid contacting stage, the result indicated that the recorded mass appeared the trend from increasing to decreasing during the period of contacting. For better analyzing the phenomenon of fiber contacting with water, we divided the A-stage into two phases, the first phase was partial contact and the second phase was full contact. An instantaneous increase in the weight was observed in the partial contact stage, and the increase was ended when it became a maximum value followed by a symmetrical decrease in the weight. After A-stage, another rapid increase in the weight occurred, followed by a regular rise until a plateau value was reached, that was B-stage. As shown in Fig.6, the imbibitions characteristics agreed with the results acquired by Pezron\cite{1}. Moreover agreements indicated that the recorded mass could be considered as a constant under the same environmental condition, which was C-stage. By reducing the liquid level, we can obtain the value of the wetting force. The characteristics time on the point of solid-liquid completely separation was much less than 1s, which was actually very shorter compared with the whole experimental time. We can thus consider here the wetting force value as a constant and equal to $w_{con}$. In addition, there was an inevitable increase for the recorded mass caused by something adhesive film of the fiber after D-stage. Finally, there was an inevitable decrease for the mass.
absorbed by fabrics via evaporation in E-stage, the curve of liquid film evaporation on 728 and 840A fabrics abided by the same law. It had been found that the resistivity of fabrics were controlled by the wettability, imbibitions of water capillary penetration of terylene or polypropylene hydrophobic fabrics were critical essential to terylene or polypropylene fabrics collectors.

Figure 6. (a) Variation of recorded mass with respect to time for water of 840A. (b) Variation of recorded mass with respect to time for water of 728.

**Resistivity and V–I curves**

In order to investigate the conductive properties of insulated hydrophobic fabric, the resistivity $\rho$ of the collector material under different WHC was studied. The corresponding V–I characteristics of fabrics collectors in the experiment were tested by air loading. The current value could be read directly from the instrument panel of the high-voltage power supply. The voltage increased from zero to the criticality value of gas breakdown or arc discharge.

| Materials | Conductors | Semiconductors | Insulators |
|-----------|------------|----------------|------------|
| Resistivity ($\rho/\Omega \cdot \text{cm}$) | $<10^{-3}$ | $10^{-7}$ to $10^{-5}$ | $>10^{9}$ |
| Examples | Aluminum, Copper, Gold | Silicon, Germanium, Gallium Arsenide | Rubber, Plastic, Porcelain, Mica |

Table 3 indicated the resistivity of several typical materials for insulators, semiconductors or conductors. When WHC was zero, that is, the resistivity of the hydrophobic fabric placed in ambient air tended to $\infty$, which belongs to the category of insulators according to the scope shown in Table 3. However, when WHC was very small (0.01L/m^2), the resistivity of the material falls sharply and is in the category of semiconductor material as shown in Fig. 7(a). According to the analysis of the research results in above, the semiconductor material had good performance when it was used as a collector. Therefore, it could be inferred that for the flexible insulating hydrophobic fabrics material selected in this paper, without considering evaporation or other losses, small-scale water consumption would meet the requirements of collector material.

As shown in Fig. 7(b), the electric field characteristics of the three kinds of collector were basically similar, and the corona voltage was all about 22kV, but there were some differences in the properties of the three kinds of materials after 30kV. In general, 728 had the strongest electric field performance followed by 840A material and glass fiber reinforced plastics (FRP), and the secondary currents were 1.9, 8, and 12mA for secondary voltage of 30, 50, and 60kV, respectively. As mentioned earlier, the penetration velocity of 728 represented obviously higher than that of 840A. Under the same conditions, the time of penetration for 728 was much shorter than that of 840A. Therefore, it would be evident to us that the wetting property of 728 was better than that of 840A. For FRP, it was impossible for water to be uniformly distributed on the surface of the solid collector when the flushing water flowed down, due to the surface tension, machining defects or flatness deviation. The field strength distribution of electrostatic field and efficiency were directly related to the conductivity of collector materials. The spontaneous immersion for water into hydrophobic fabric collectors would be of
practical importance for the purpose of uniform water film distribution via capillary flow, thus would allow lower water addition rate and non-interrupted operation for industrial use.

Summary

The experiment was designed to investigate the interrelation between water penetration and transformation of conductivity for terylene or polypropylene collection electrode as collection electrodes. The results show that drop spreading existed in imbibitions experiments when the hydrophobic fabrics were contacted with water. Five different physical stages occurred successively during the imbibitions behavior experiments, namely solid-liquid contact(A), imbibition(B), steady balance(C), solid-liquid separation(D) and evaporation of external liquids(E) stages. The phase of solid-liquid contact reflects the equilibrium relationship between the wetting tension and the buoyancy of the liquid. The resistivity of polypropylene fibrous decreased to $2.4 \times 10^5 \Omega \cdot cm$ when WHC was 0.01Lm$^{-2}$, thus would be enough to meet a demand or requirement for collectors. The discharge current by polypropylene collection electrode was 5~20 percent higher than that by FRP. The spontaneous immersion for water into hydrophobic fabric collectors would be of practical importance for the purpose of uniform water film distribution via capillary flow, thus would allow lower water addition rate and non-interrupted operation for industrial use.

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