SATURATION RATE DETERMINATION DURING ASCENDANT, HORIZONTAL AND DESCENDANT CAPILLARY RISE USING ELECTRICAL RESISTIVITY

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Abstract: *In this paper, a saturation rate during the capillary rise of a textile fabric was determined. A mathematical model based on the Archie's law, considering the electrical resistivity, saturation rate and fabric tortuosity was established. In order to determine the saturation exponent a calibration method was introduced. According to this method the spatiotemporal distribution of the saturation rate during the capillary rise is presented. This method was also used to evaluate the saturation rate during the horizontal and downward capillary rise. It was found that the saturation rate remains constant for the case of the horizontal and descending impregnation.*

Keywords: *capillary rise, electrical resistivity, horizontal-downward capillary, saturation rate.*

1 INTRODUCTION

The comfort afforded by textile fabrics can be improved by understanding the liquid transport mechanism. In capillary flow through textile fabrics, the constitute yarns are responsible for the main portion of the wicking action [1, 2]. Therefore, many researches have been conducted to study the wicking behaviour in textile structure. Among the extensive research in this field, textile yarns were treated either as porous media [3, 4], the liquid transport through which can be described by Darcy's law, or as capillary tubes, the liquid flow through which can be modelled by Lucas–Washburn kinetics. In the first case, however, the characteristic parameters, such as permeability, are difficult to quantify and are always obtained empirically [5]. In the second case, similarly, the effective radius of the capillary tube, the effective contact angle, etc., are also determined by fitting the experimental data [6]. A literature review, previously mentioned [1-8], shows that although broad research has been carried out in this area, a procedure to determine the saturation during capillary flow through textile based is still lacking.

In this work, the saturation rate during the capillary rise is determined using an electrical resistivity method. A theoretical model was developed based on the Archie's law. An experimental validation showed that our model can determine correctly the spatiotemporal distribution of saturation rate in textile structure.

2 FABRIC SATURATION DETERMINATION USING ELECTRICAL RESISTIVITY

There is an analogy between the laws of fluid mechanics and those of electrical conduction. The difference in pressure in a pipe is in fact the analog of a potential difference across a conductor, while the fluid flow is the analog of the electric current. In both cases, the relationship between pressure/flow difference and potential/current difference depends on the geometry (form and length) of the pipe or conductor.

Archie's law [9] has been the standard method for relating the conductivity of a clean reservoir rock to its porosity and the conductivity of the fluid saturating its pores for over 60 years. Initially, it was used as an empirical relationship for a narrow range of rocks and porosities, it has found wide application. It has been verified recently by analytical methods for certain special cases [10, 11] and has been extended for use when the surface conduction is significant, such as at low salinities and in clay-bearing lithofacies [12]. One form of the traditional Archie's law can be expressed as [13]:

$$R_{e-m} = \frac{R_{e-water}}{\tau \varepsilon^{m} S^{n}}. \quad (1)$$

where R_{e-m} [Ω.m] is the bulk effective resistivity of the porous material; $R_{e\text{-}Water}$ [Ω.m] is the resistivity of the liquid occupying the pores; ε is the porosity which is assumed to be fully saturated (i.e., identical to the volume fraction of the fluid phase); S is saturation rate, τ is the tortuosity, m is the cementation exponent and n is the saturation exponent (usually close to 2).

The cementation exponent m, also called compacity factor and usually in the range 1.3–2.5, is an index of the pores sizes in the porous media [13]. It has been demonstrated by Keller [14] that the compacity exponent is closely related to the porous compacity level, pores size and distribution.

The use of Archie's law requires the porosity and liquid resistivity determination. Moreover, the exponents m and n are empirical and determined for each sample. Thus, it is necessary to carry out calibration experiments determining these various parameters.

Other researchers evaluated the saturation rate S as a function of the resistivity index I_R, (second Archie's law) defined by:

$$I_R = \frac{R_{e-m}}{R_{e-sat}} = \frac{1}{S^n}. \tag{2}$$

where, $R_{e\text{-}sat}$ [Ω.m] is the resistivity of the saturated material.

By plotting $\ln\left(\frac{R_{e-m}}{R_{e-sat}}\right)$ as a function of saturation rates the constant n is determined. The exponent of "Archie saturation" n is also close to 2 but can reach 10 [15].

3 CALIBRATION METHODOLOGY

A calibration is carried out for each sample in order to evaluate the saturation rates by measurement of electrical resistivity for each saturation rate. Thus, a sample (dimensions 5×5 cm) with dried mass m_d [g] is impregnated in distilled water and then transferred to a support. The mass of the sample is continuously recorded by an electrical balance in order to determine the saturation rate.

The electrical resistivity was measured using the 4339B high-resistance meter from Agilent® (Figure 1).

The non-conductive grid allows the sample to be dried through both sides. Each sample is placed freely on the drying support and not tensioned to avoid deformations that can modify the size of the pores. During drying, wet mass m_w [g] decreases. The saturation rate S is calculated as follows:

$$S = \frac{m_w - m_d}{m_d}. \tag{3}$$

Thus, the calibration procedure consists in measuring the resistivity as a function of the different saturation rates.

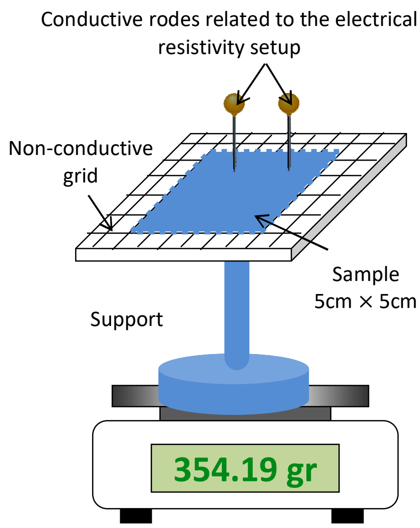

Figure 1 Calibration setup for sample electrical resistivity

Figure 2 illustrates the sample calibration for the saturation exponent n determining. It is noticed that the regression line of the curve is linear with a coefficient of determination R^2 = 0.984 and n = 2.5351.

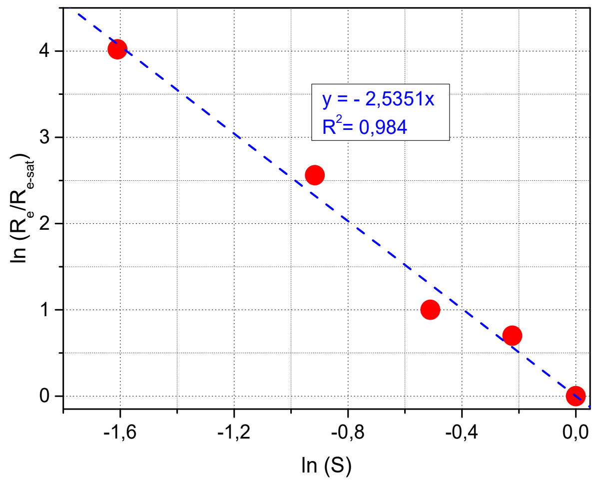

Figure 2 Calibration a sample for determining the saturation exponent n

4 SATURATION RATE DETERMINATION DURING CAPILLARY RISE FROM INFINITE RESERVOIR

A series of experiments on a plain knitted structure was conducted with distilled water as wicking liquid. The experimental apparatus for vertical capillary rise [6]. The experiments were conducted in a standard atmosphere of 20±2°C and 65±2% relative humidity, and the samples were conditioned for 24 hours before testing.

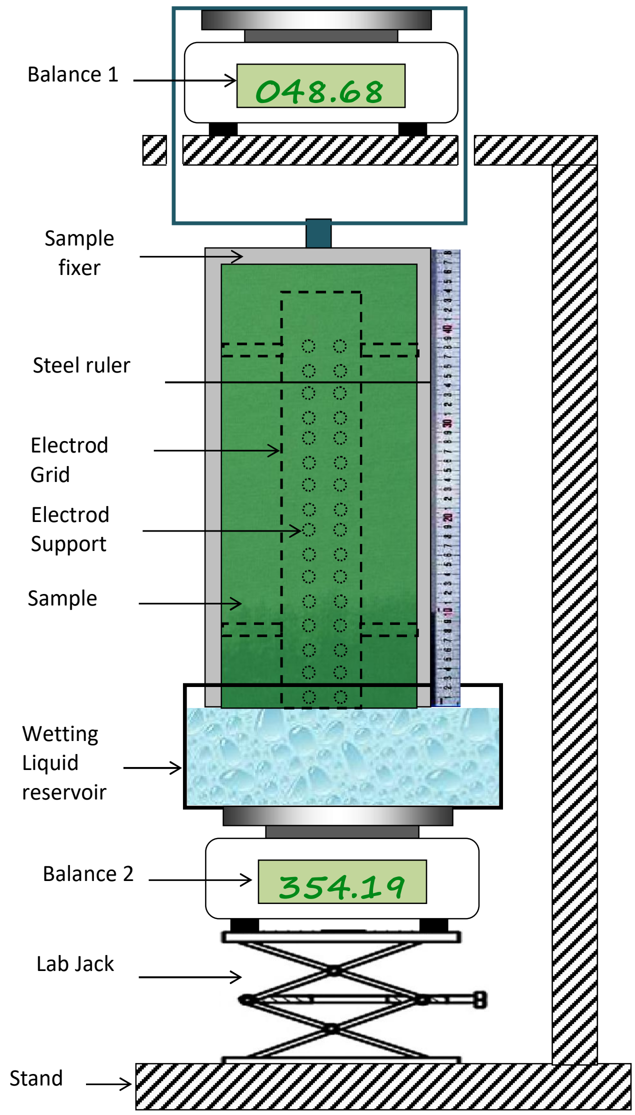

Figure 3 Experimental apparatus for capillary rise considering evaporation [6]

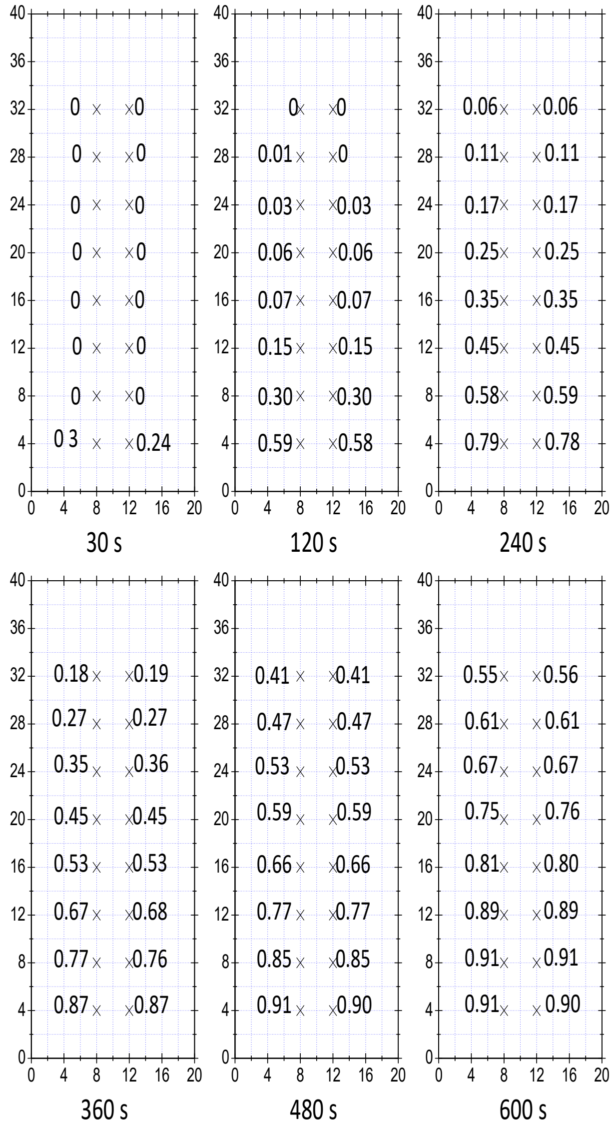

Figure 4 Spatiotemporal distribution of saturation rate in the case of a capillary rise test at 4 cm steps

In the apparatus, the lab jack was used to hoist the liquid reservoir containing the wicking liquid, and the steel ruler to measure the wicking height.

Figure 3 shows the Spatiotemporal distribution of saturation in width and height of a capillary rise test. For the same height, the saturation rate is identical which implies the structure is the same according to the width. According the Figure 3, not surprisingly, the penetration velocity of liquid in early stage is much higher than in subsequent stages. With time passing, the advancement of liquid becomes slower and slower until equilibrium is established. Figure 4 illustrates Spatiotemporal distribution of saturation rate in the case of a capillary rise test at 4 cm steps.

5 SATURATION RATE DETERMINATION DURING HORIZONTAL AND DOWNWARD CAPILLARY FROM INFINITE RESERVOIR

Figure 5 illustrates the variation in saturation rate in the case of horizontal and descending capillary at different vertical positions *ha* at 4 cm and at 8 cm.

In the case of h_a = 4cm, the average saturation rate is about 0.6675 with a standard deviation of 0.0093 and a coefficient of variation of 1.394%. Whereas for h_a = 8 cm, the average saturation rate is about 0.4106 with a standard deviation of the order of 0.0068 and a coefficient of variation of 1.65%. Therefore it can be concluded that the saturation rate remains constant for the case of the horizontal and descending impregnation.

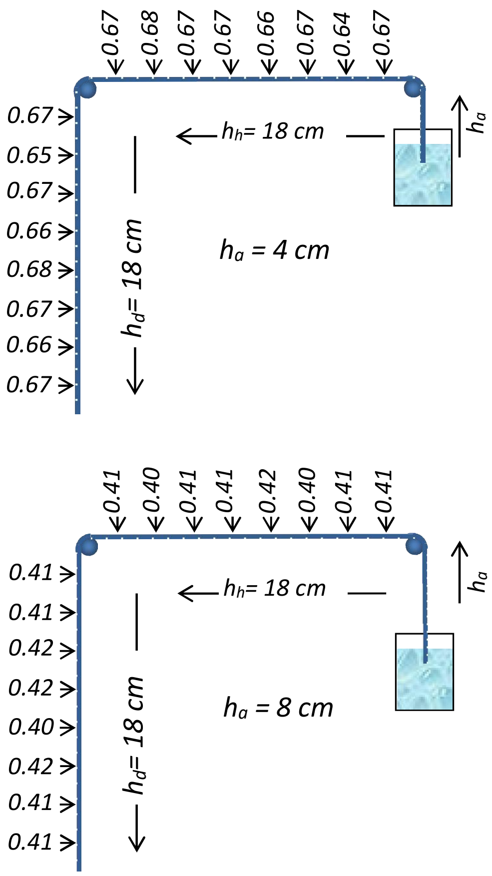

Figure 5 Saturation rate at 2 cm interval: horizontal h_h and downward capillary from infinite reservoir h_d (ascendant capillary h_a = 4 cm and 8 cm)

In addition, the average saturation rate is decreasing by increasing the distance from the reservoir (when h_a increases). Indeed, by increasing h_a, the saturation rate becomes smaller at the level of the horizontal and descending impregnation portion (see Figure 3). This is due to the effect of gravitational forces.

6 CONCLUSION

The saturation rate during capillary rise was investigated. Using modified Archie's law, the saturation was determined based on the electrical resistivity of wetted textile fabric. The calibration method was carried out for each sample to determine the saturation exponent *n* before testing.

The spatiotemporal repartition of the saturation rate during the capillary rise was presented. This method was also used to evaluate the saturation rate during the horizontal and downward capillary rise. It was found that the saturation rate remains constant for the case of the horizontal and descending impregnation. In addition, the average saturation rate is decreasing by increasing the distance from the reservoir when h_a increases. Wicking in textile materials is very complicated and the mechanism has not been fully understood until now.

Nevertheless, this research attempts to gain an insight into this area and to construct a framework for further studies. Modeling the fabric permeability during wicking will form the subject of subsequent researches.

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