Gilbert De Mey[1], Ilda Kazani[2, 3], Majlinda Hylli[2], Pellumb Berberi[4]
[1] Department of Electronics and Information Systems, Ghent University, Technologiepark 126, 9052 Ghent, Belgium
[2] Department of Textile and Fashion, Polytechnic University of Tirana, Sheshi Nënë Tereza 1, Tirana, Albania
[3] Albanian Young Academy, Shëtitoria Murat Toptani 1000, Tirana, Albania
[4] Department of Engineering Physics, Polytechnic University of Tirana, Bulevard Dëshmorët e Kombit 4, Tirana, Albania

Influence of Humidity on the Electric Resistivity of Leather: Mathematical Modelling

Matematično modeliranje vpliva vlažnosti na električno upornost usnja

Short scientific article/*Kratki znanstveni prispevek*
Received/*Prispelo* 11-2022 • Accepted/*Sprejeto* 12-2022

Corresponding author/*Korespondenčna avtorica:*
Assoc Prof dr. Ilda Kazani
E-mail: ikazani@fim.edu.al
ORCID ID: 0000-0002-5727-5553

Abstract

A mathematical model is presented to simulate the electric resistivity of leather samples as a function of humidity. It will be shown that absolute and not relative humidity is the crucial parameter. The model assumes that the leather includes channels that can absorb water from the surrounding environment. This effect primarily determines the electric conductivity of the leather samples. The theoretical results from the model are quite closely in line with experimental measurements.
Keywords: electric resistivity, leather, humidity, modelling

Izvleček

Predstavljen je matematični model za simulacijo električne upornosti vzorcev usnja kot funkcije vlažnosti. Poudariti je treba, da je odločilni parameter absolutna in ne relativna zračna vlažnost. Model predvideva, da usnje vsebuje kanale (kapilare), ki lahko absorbirajo vodo iz okolice. Ta učinek predvsem določa električno prevodnost vzorcev usnja. Teoretični rezultati modela se dobro ujemajo z eksperimentalnimi meritvami.
Ključne besede: električna upornost, usnje, vlaga, modeliranje

1 Introduction

Due to 21st century technology, we must adapt to smart products offered by the market where tablets, computers, most mobile screens and smartwatches operate with a capacitive touch screen (finger-touch method) [1]. One practical application is the use of a touch screen when wearing leather gloves. These screens use the electric conductivity of the fingertip to increase the electric capacitance in a certain area of the screen. If gloves are worn, they should also be electrically conductive. It will be shown later that pure leather is a poor electric conductor. Leather will however, become conductive by absorbing water from ambient humid air or by diffusion from the finger. This is also true, depending on weather, climate or different conditions, where the finger-touch method is not possible and a conductive glove is very important [2–4].

Furthermore, the rapid growth of electrical and electronic devices and accessories that emit electromagnetic energy in different frequency bands has led to an increase in exposure to EM radiation, which can be harmful for human health. It was determined from literature that electrically conductive textiles are preferred for shielding applications primarily due to their good shielding properties and numerous advantages [5]. Although there are different studies about electromagnetic shielding textiles in literature, there is an urgent need to develop electromagnetic interference (EMI) shielding materials [6].

Moreover, different groups have worked on textile antennas [7–10] and leather antennas [11] for wearables, in which the conductivity is a prerequisite. Therefore, in order to make resistive traditional leather conductive, different groups have worked with different methods [2–4, 12–14].

In previous contributions, sheep crust leather was coated with polypyrrole using the double in-situ polymerization method and the electrical resistivity of conductive leather using the "multiple-step method" [15–16] in different air temperature and humidity conditions was measured [17].

In this paper, a theoretical analysis of the influence of humidity on the electric resistivity of leather was performed. The mathematical theory of this method will be outlined in the next section.

2 Mathematical model

In order to set up a mathematical model, a closer look must be taken at the experimental results shown in Figure 1. If the two figures (Figures 1a and 1b) are compared, it is clear that relative humidity *RH* is no longer a suitable parameter. On the other hand, Figure 1b shows a good relationship with absolute humidity. In a previously published paper, these data were fitted to $H^{-1.042}$ or $H^{-1.059}$, depending on whether sheets were included or only strips were taken into account [17]. The measuring technique was especially designed for textile samples and has been described extensively in literature [15–16].

These results are not surprising at all. Relative humidity is used to describe the environmental effect of air on the human body. Moreover, relative humidity is rather easy to measure. However, this paper deals with the electric conductivity of leather. Electric conductivity is determined by the intrinsic conductivity of leather and the amount of absorbed water molecules. The latter is simply absolute humidity usually expressed in g/kg or grams of water per kilogram air. We must therefore limit our investigation to modelling electric resistivity as a function of absolute humidity *H*.

If we extrapolate the fitting $H^{-1.042}$ or $H^{-1.059}$ [17] to low values of *H*, it is clear that the resistivity of intrinsic leather must be very high. We would expect it should be at least one order of magnitude higher than the maximum value of 500 Ωm shown in Figure 1b.

Firstly, the experimental fittings $H^{-1.042}$ or $H^{-1.059}$ [17] suggest that, theoretically speaking, it could be just *1/H*. Secondly, a closer look at Figure 1b tells us that humidity *H* has a tremendous influence on resistivity. The values vary between 65 Ωm and 437 *Ωm*. The conclusion is obvious: electric conduction is mainly determined by the amount of absorbed water, and the

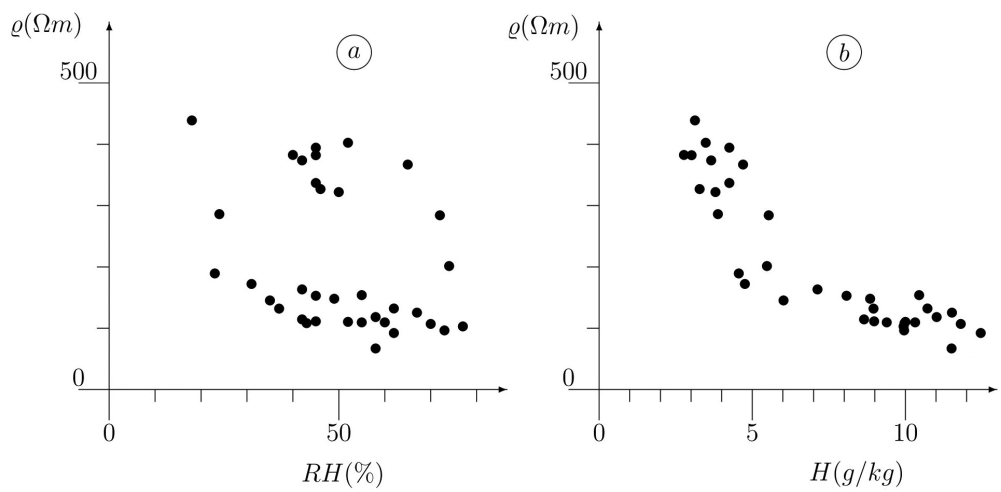

Figure 1: Variation of resistivity ρ vs. (a) relative humidity RH and (b) absolute humidity H [17]

conductivity of completely dry leather must be very low. These results also prove that there must be channels inside the leather filled with water. These channels provide electro conducting wires between the two electrodes. The word "channel" should be interpreted in a broad sense. A surface layer of water will also conduct electricity between the two electrodes.
A simple model is shown schematically in Figure 2. The two rectangular electrodes, with an area expressed as $S = b \times d$, are at distance a. Conducting channels now connect the two electrodes. Each channel has a cross section of ΔS and a length of a. It is obvious that the conductivity of the channel is proportional to absolute humidity: $\sigma_{channel} = \alpha H$. Conductance G between the two electrodes is then given by the equation:

$$G = G_{leather} + G_{Channels} = \sigma_{leather}\frac{bd}{a} + N\sigma_{channel}\frac{\Delta S}{a} \quad (1)$$

Conductivity σ, which is the inverse of resistivity $(\sigma = 1/\rho)$ is then found using the equation:

$$\sigma = G\frac{a}{bd} = \sigma_{leather} + N\sigma_{channel}\frac{\Delta S}{bd} = \sigma_{leather} + \frac{N\alpha\Delta S}{bd}H \quad (2)$$

Resistivity ρ is then the inverse of equation (2):

$$\rho = \frac{1}{\sigma} = \frac{1}{\sigma_{leather} + N\sigma_{channel}\frac{\Delta S}{bd}} = \frac{\rho_{leather}}{1+\beta H} \quad (3)$$

Where $\rho_{leather} = 1/\sigma_{leather}$. Parameter β is given by the equation:

$$\beta = \frac{N\alpha\Delta S\rho_{leather}}{bd} \quad (4)$$

As already stated, resistivity $\rho_{leather}$ is very high, so that (3) can be approximated using the equation:

$$\rho_{approx} = \frac{\rho_{leather}}{\beta H} \quad (5)$$

This result is quite close to the fittings $H^{-1.042}$ or $H^{-1.059}$ used in [17]. Although this mathematical model is very simple (all channels have an equal length and cross section), it will help us explain the experimental results, as will be seen below.
The experimental results shown in Figure 1b have been redrawn in Figure 3 on a double logarithmic scale. A $1/H$ curve, such as (5), is then represented by a straight line. The experimental data can be fitted quite well to the equation 6, where the resistivity ρ is expressed in Ωm and the absolute humidity H in g/kg::

$$\rho_{approx} = \frac{1148}{H} \rightarrow \frac{\rho_{leather}}{\beta} = 1148 \quad (6)$$

A second fitting using (3) was only possible for $\rho_{leather}$ values > 10000 Ωm, as also shown in Figure 3. We can thus conclude that the fitting using (3) helps us to achieve a lower limit for the resistivity of intrinsic leather. If we assume for a moment $\rho_{leather}$ = 10000 Ωm, we can determine the parameter β to be given by β = 8.7108. Note that higher values of $\rho_{leather}$ also provide good fittings with the measurements.

3 Conductivity plot

Equations (2) and (3) suggest that it might be more obvious to plot conductivity σ as a function of absolute humidity H. We should then expect a straight line in a linear plot as shown in Figure 4. A linear fitting has been performed using the least squares approximation. The result is:

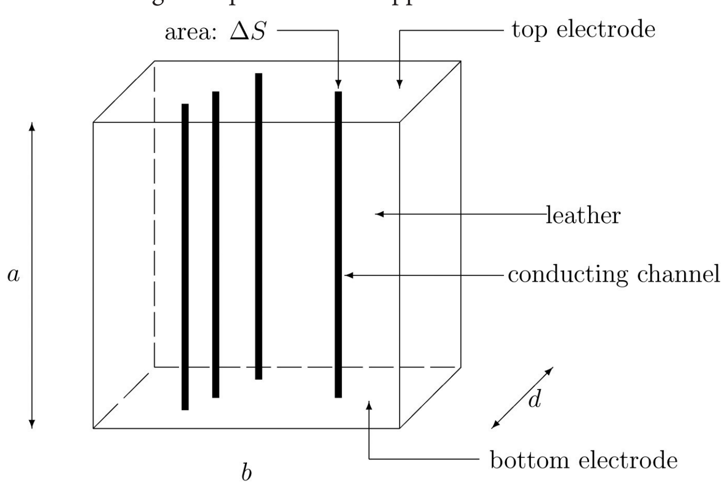

Figure 2: Model used to explain the electric resistivity of leather samples

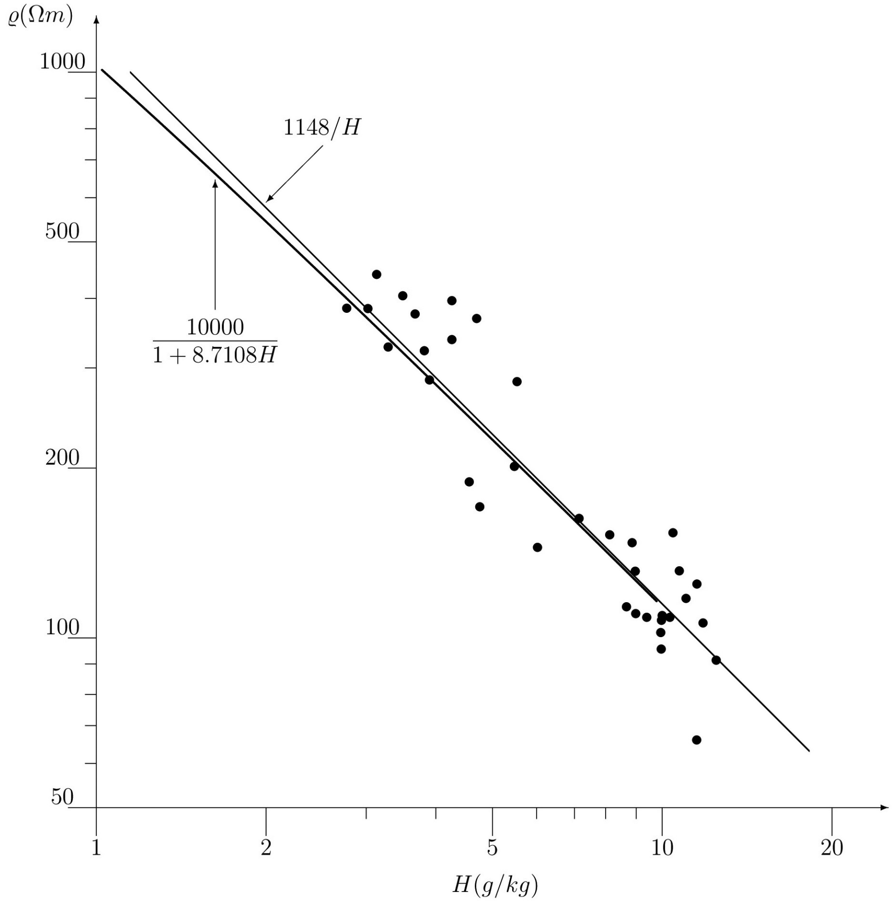

Figure 3: Double logarithmic plot of resistivity ρ vs. absolute humidity H

$$\sigma_{approx} = -0.0001975 + 0.00090883\,H\left(\frac{\mathrm{S}}{\mathrm{m}}\right) \quad (7)$$

As in the previous section, an extrapolation towards $H \to 0$ should inform us about the intrinsic conductivity of the leather. However, the fitting (7) gives us a negative number, which physically makes no sense. However, a closer view of Figure 4 reveals that the negative number in (7) is caused by inevitable errors due to the fitting procedure. We can also interpret these results as the zero conductivity of completely dry leather. Nevertheless, the conductivity plot is not suitable for obtaining a limiting value of leather conductivity.

For higher values of *H*, we can omit the negative number so that:

$$\sigma_{approx} = 0.00090883\,H\left(\frac{\mathrm{S}}{\mathrm{m}}\right) \quad (8)$$

from which we get easily:

$$\frac{1}{\sigma_{approx}} = \frac{10^4}{9.0833\,H} = \frac{1100.3}{H} \quad (\Omega\mathrm{m}) \quad (9)$$

which is very close to the approximation *1148/H* found in (6).

The conclusion is thus obvious: the conductivity plot is suitable for finding a simple relation such as (7), but we cannot find an upper limit for the conductivity of pure intrinsic leather. Using the resistivity plot presented in the previous section, it was possible to find a lower limit for leather resistivity of 10000 Ωm, which corresponds to a conductivity of 0.0001 S/m.

4 Discussion

In order to set up a mathematical model, a closer look must be taken at the experimental results shown in Figure 1. If we compare the model outlined so far, it is a highly simplified version of the real situation. In practice, not all conducting channels will connect two electrodes by a straight line. Some channels will be wider, and thus able to absorb more water from the surrounding air. We assume, for example, that half of the channels have a

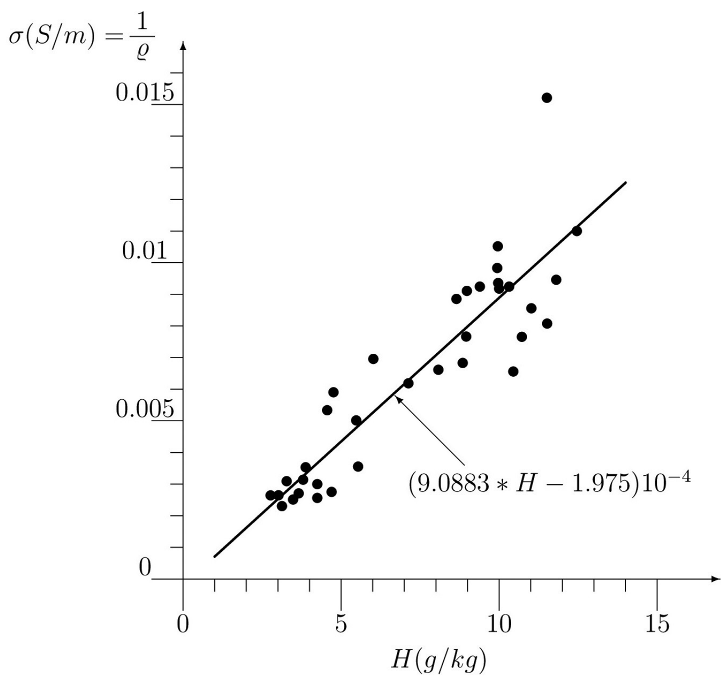

Figure 4: Plot of conductivity σ as a function of absolute humidity H

length of *a* and the other half have a double length of *2a*, as shown schematically in Figure 5.

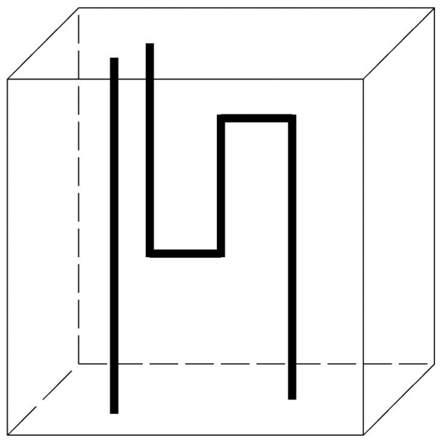

Figure 5: Channels with different lengths: a and 2a

Equation (1) must then be replaced by the equation:

$$G = G_{leather} + G_{channels} = \sigma_{leather}\frac{bd}{a} + \frac{N}{2}\sigma_{channel}\frac{\Delta S}{a} + \frac{N}{2}\sigma_{channel}\frac{\Delta S}{2a} \quad (10)$$

Equation (3) still remains valid. The difference is that coefficient β is now given by the equation:

$$\beta = \frac{3N\alpha\Delta S\rho_{leather}}{4bd} \quad (11)$$

This proves that the theory outlined above remains valid, and only the numerical value of β must be adjusted.

Obviously, the actual situation is much more complicated than channels with lengths of *a* and *2a*. In practice, channels are randomly distributed, may have different lengths and sections, and are oriented in all possible directions. Only channels connecting two electrodes can contribute to detectable resistivity. Even when probability distributions are introduced for channels lengths as the cross-sections in equation (2), we still arrive at the same result (3), except that the expression for coefficient β will be much more complicated than (4). The only assumption that may not be changed is: $\sigma_{channel} = \alpha H$. In other words: electric conductivity $\sigma_{channel}$ is proportional to absolute humidity *H*, and remains the basic assumption of our model.

5 Conclusion

A theoretical investigation of the electric conductivity of leather samples as a function of the absolute humidity is presented in this paper. In order to set up a mathematical model, a closer look must be taken at the experimental results. A mathematical model was presented to explain the electric conductivity of leather samples as a function of absolute humidity. It was also made clear that there is no direct correlation between resistivity and relative humidity. Moreover, it was possible to find a lower limit for the resistivity of intrinsic leather samples. It is clear that the same approach can be used to model the resistivity of other solid materials with channels that can absorb water from ambient humid air. Alternatively, such a method can also be used to indicate the porosity of a material.

References

1. NAM, H., SEOL, K.H., LEE, J., CHO, H., JUNG, S.W. Review of capacitive touchscreen technologies: overview, research trends, and machine learning approaches. *Sensors*, 2021, **21**(14), 4776, doi: 10.3390/s21144776.
2. YANG, C., WANG, J., LI, L. A novel approach for developing high thermal conductive artificial leather by utilizing smart electronic materials. *Textile Research Journal*, 2017, **87**(7), 816–828, doi: 10.1177/0040517516641356.
3. WEGENE, J.D., THANIKAIVELAN, P. Conducting leathers for smart product applications. *Industrial & Engineering Chemistry Research*, 2014, **53**(47), 18209–18215, doi: 10.1021/ie503956p.
4. HONG, K.H. Preparation of conductive leather gloves for operating capacitive touch screen displays. *Fashion & Textile Research Journal*, 2012, **14**(6), 1018–1023, doi: 10.5805/KSCI.2012.14.6.1018.
5. DURAN, D., KADOĞLU, H. Electromagnetic shielding characterization of conductive woven fabrics produced with silver-containing yarns. *Textile Research Journal*, 2015, **85**(10), 1009–1021, doi: 10.1177/0040517512468811
6. WANG, Y., PENG, H.K., LI, T.T., SHIU, B.C., ZHANG, X., LOU, C.W., LIN, J.H. Layer-by-layer assembly of low-temperature in-situ polymerized pyrrole coated nanofiber membrane for high-efficiency electromagnetic interference shielding. *Progress in Organic Coatings*, 2020, **147**, 105861, doi: 10.1016/j.porgcoat.2020.105861.
7. HERTLEER, C., ROGIER, H., VALLOZZI, L., VAN LANGENHOVE, L. A textile antenna for off-body communication integrated into protective clothing for firefighters. *IEEE Transactions on Antennas and Propagation*, 2009, **57**(4), 919–925, doi: 10.1109/TAP.2009.2014574.
8. VALLOZZI, L., VAN TORRE, P., HERTLEER, C., ROGIER, H., MOENECLAEY, M., VERHAEVERT, J. Wireless communication for firefighters using dual-polarized textile antennas integrated in their garment. *IEEE Transactions on Antennas and Propagation*, 2010, **58**(4), 1357–1368, doi: 10.1109/TAP.2010.2041168.
9. DEL-RIO-RUIZ, R., LOPEZ-GARDE, J.M., MACON, J.L., ROGIER, H. Design and performance analysis of a purely textile spiral antenna for on-body NFC applications. In *2017 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*, 2017, 1–3, doi: 10.1109/IMWS-AMP.2017.8247427.
10. JIANG, Y., XU, L., PAN, K., LENG, T., LI, Y., DANOON, L., HU, Z. e-Textile embroidered wearable near-field communication RFID antennas. *IET Microwaves, Antennas & Propagation*, 2019, **13**(1), 99–104, doi: 10.1049/iet-map.2018.5435.
11. MITILINEOS, S.A., KALLIVRETAKI, A.E., VASSILIADIS, S., KAZANI, I., GUXHO, G., DASSONVILLE, F., KONCAR, V. A wearable NFC antenna sewn on leather substrate for immersive IoT applications. *Textile & Leather Review*, 2022, **5**, 70–84, doi: 10.31881/TLR.2022.03.
12. SHIN, E.J., HAN, S.S., CHOI, S.M. Fabrication of highly electrical synthetic leather with polyurethane/poly(3,4-ethylene dioxythiophene)/poly(styrene sulfonate). *The Journal of The Textile Institute*, 2018, **109**(2), 241–247, doi: 10.1080/00405000.2017.1337296.
13. BAO, Y., FENG, C., WANG, C., MA, J., TIAN, C. Hygienic, antibacterial, UV-shielding performance of polyacrylate/ZnO composite coatings on a leather matrix. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2017, **518**, 232–240, doi: 10.1016/j.colsurfa.2017.01.033.
14. HYLLI, M., SHABANI, A., KAZANI, I., BEQIRAJ, E., DRUSHKU, S., GUXHO, G. Application of double in-situ polimerization for changing the leather properties. In *Book of Proceedings of 8th International Textile Conference*, Tirana, Albania, 2018, 42–47.
15. BERBERI, P.G. A new unified method for measurment of electrical resistivity of textile assemblies. In *Proceedings of ESA Annual Meeting, Boston University, June 23–25, 1999,* 121–134.
16. BERBERI, P.G. Effect of processing on electrical resistivity of textile fibers. *Journal of Electrostatics*, 2001, **51–52**, 538–544, doi: 10.1016/S0304-3886(01)00112-7.
17. KAZANI, I., HYLLI, M., BERBERI, P. Electrical resistivity of conductive leather and influence of air temperature and humidity. *Tekstilec*, 2021, **64**(4), 298–304, doi: 10.14502/Tekstilec2021.64.298-304.